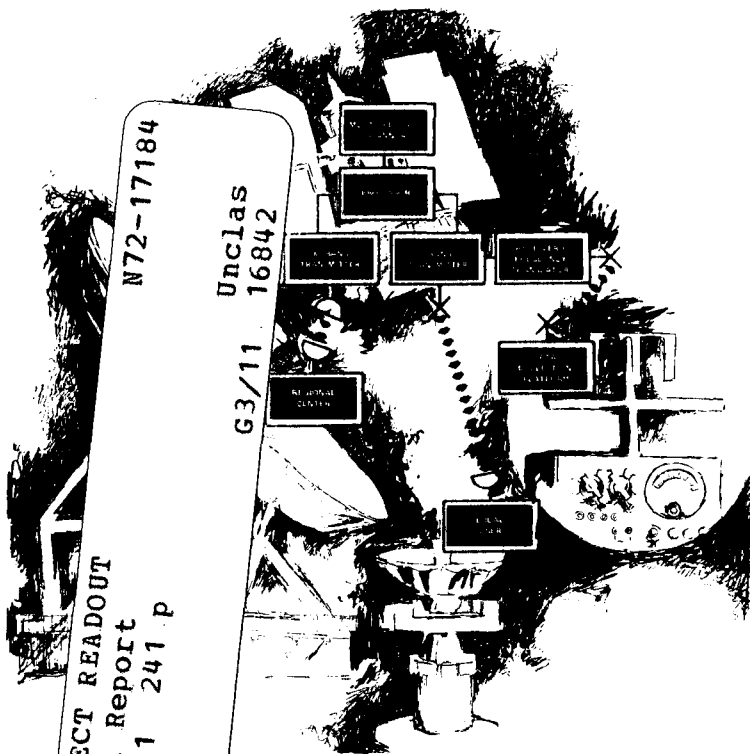
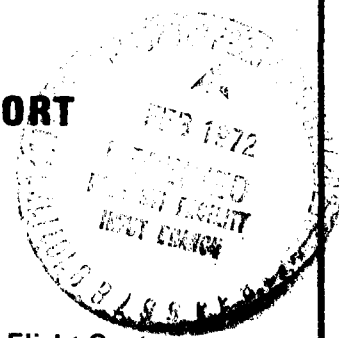


7640-72-001
December 1971

ERTS
DIRECT
READOUT
GROUND
STATION
STUDY



FINAL REPORT



Prepared for
Goddard Space Flight Center
Greenbelt, Maryland
Under Contract Number NAS5-21622

**Prepared by
Systems Engineering Department
Surface Systems Operations
Radiation Systems Division**

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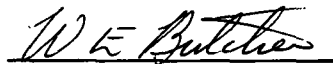
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FINAL REPORT

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Prepared by

Systems Engineering Department
Surface System Operation
Radiation Systems Division

A handwritten signature in cursive script, reading "W E Butcher", is positioned above a horizontal line.

Dr. W. E. Butcher
Project Manager

Prepared for

Goddard Space Flight Center
Greenbelt, Maryland
Under Contract Number NAS5-21622

TABLE OF CONTENTS

Section	Title	Page
1.0	INTRODUCTION	1-1
2.0	SYSTEM SUMMARY	2-1
2.1	Scope of Study	2-1
2.2	Study Results	2-2
2.3	Spacecraft Summary	2-4
2.4	RCC Summary	2-4
2.5	LUT Summary	2-10
3.0	GENERAL SYSTEM CONSIDERATIONS	3-1
3.1	Geometrical Constraints	3-2
3.2	User Considerations	3-12
3.2.1	General Considerations	3-12
3.2.2	Quantity of Data	3-16
3.2.3	Timeliness of Data	3-18
3.2.4	Resolution Requirements	3-19
3.2.5	Number of Spectral Bands	3-20
3.3	Sensor Characteristics	3-20
3.3.1	ERTS-A Sensors	3-21
3.3.2	Possible 100-200 Mb/s Sensor Characteristics	3-25
3.3.3	Data Collection System (DCS) Characteristics	3-27
3.4	Frequency Selection Considerations	3-28
3.4.1	Summary of Frequency Selection Criteria	3-28
3.4.2	Allocation Considerations	3-29
3.4.3	Performance Factors	3-33
3.4.4	Component Availability	3-46
4.0	SYSTEM ANALYSIS	4-1
4.1	Regional Collection Center (RCC)	4-1
4.1.1	Guidelines and Assumptions	4-1
4.1.2	Modulation/Multiplexing Considerations	4-2
4.1.3	Link Analysis	4-12
4.1.4	Link Summary	4-19
4.2	Local User Terminal (LUT)	4-20
4.2.1	Guidelines and Assumptions	4-20
4.2.2	System Alternatives	4-20

TABLE OF CONTENTS (Continued)

Section	Title	Page
4.2.3	Link Analysis for LUT	4-22
4.2.4	Channel Coding Considerations for LUT	4-36
4.2.5	DCS Data	4-37
5.0	SPACECRAFT CONFIGURATION	5-1
5.1	General Description	5-1
5.2	Data Collection System	5-4
5.3	EOS Transmitters	5-6
5.3.1	Spacecraft Transmitter Technology	5-6
5.3.2	Mode II Transmitter	5-8
5.3.3	Mode I Transmitter	5-9
5.4	EOS Antenna System	5-10
5.5	Data Handling and Multiplexing	5-12
5.5.1	Baseline Spacecraft System	5-12
5.6	Spacecraft Parameter Summary	5-14
6.0	REGIONAL COLLECTION CENTER (RCC) CONFIGURATION .	6-1
6.1	RCC General Characteristics	6-1
6.2	Subsystem Descriptions	6-3
6.2.1	Antenna Feed and Microwave Subsystem	6-3
6.2.2	Antenna Pedestal and Reflector	6-9
6.2.3	Antenna Control Subsystem (ACS)	6-10
6.2.4	Receiver Subsystem	6-16
6.2.5	Data Processing Subsystem	6-21
6.2.6	Recorder Subsystem	6-30
6.3	Cost Estimates	6-32
7.0	LOCAL USER TERMINAL (LUT) CONFIGURATION	7-1
7.1	LUT General Characteristics	7-1
7.2	LUT Subsystems	7-4
7.2.1	Antenna and Structure Subsystem	7-4
7.2.2	Servo Subsystem	7-5
7.2.3	Receiver Subsystem	7-7
7.2.4	Recorder Subsystem	7-7
7.2.5	Display Subsystem	7-8
7.3	Cost Estimates	7-9

TABLE OF CONTENTS (Continued)

Section	Title	Page
8.0	CONCLUSIONS AND RECOMMENDATIONS	8-1
	APPENDICES	
A	SPECIAL TECHNOLOGY AREAS	A-1

1.0

INTRODUCTION

This final report on Contract NAS5-21622 presents the results of the ERTS Direct Readout Ground Station Study, conducted by the Systems Division of Radiation Incorporated, Melbourne, Florida. It has been the general objective of this study to analyze and perform trade-off studies relative to future Earth Resource Technology Satellite (ERTS) type systems. Radiation is pleased to have had the opportunity for continued participation in this class of programs being designed to increase understanding of and benefits from the environment.

A system configuration which provides for a wide variety of user requirements is described herein. Two distinct user types are considered and optimized configurations are provided. Independent satellite transmission systems allow simultaneous signal transmission to Regional Collection Centers via a high data rate channel and to local users who require near real time consumption of lower rate data. In order to maximize the ultimate utility of this study effort, a parametric system description is given such that in essence a shopping list is provided. To achieve these results, it has been necessary to consider all technical disciplines associated with high resolution satellite imaging systems including signal processing, modulation and coding, recording, and display techniques. In short, a total systems study has been performed.

This report is divided into 8 major headings which present the primary study results. Supporting information and reference data is found in the Appendices.

Section 2.0 presents a general summary and overview of the study objective and study results. General considerations are found in Section 3.0. The topics discussed in this section include system geometry, user requirements, sensor characteristics, and factors which influence link design. Section 4.0 utilizes the basic information given in Section 3.0 to perform the system analysis necessary to determine the required system alternatives and configurations. Details of the spacecraft, Regional Collection Center, and Local User Terminal Configurations which evolve from the analysis are presented in Sections 5.0, 6.0, and 7.0 respectively. Finally, conclusions and recommendations are summarized in Section 8.0.

2.0

SYSTEM SUMMARY

Development of the Earth Resources Technology Satellites (ERTS) has produced a tremendous amount of well-founded enthusiasm in a variety of scientific and potential user communities. Such satellites as ERTS will allow efficient and accurate mapping of resources, detection of pollution, may direct fishing fleets to the most productive areas, along with a wide variety of other applications. The first satellite of this series, ERTS-A, will be launched in the Spring of 1972 and will carry both TV cameras and a multi-spectral scanner (MSS). These on-board sensors will provide high resolution image data to be transmitted to ground processing centers and ultimately distributed to a variety of users and experimenters. In addition, ERTS-A has the capability of relaying data from remotely located ground based sensors to the ground collection center, via the Data Collection System (DCS), thus providing a more efficient and complete monitoring system.

While the precise characteristics of any future operational Earth Resource Observation System (EROS) and Earth Observatory Satellites (EOS) are dependent upon experimental results obtained with ERTS, planning and study for these next generation systems has already been initiated. The study effort described in this report represents a major element of this planning. A diversity of technology areas and system alternatives have been considered and analyzed to evolve to the results presented herein.

2.1

Scope of Study

The basic study objective was to perform a parametric analysis of spacecraft and ground station configurations, to match these configurations against requirements for future operational ERTS type systems, and to perform the appropriate trade-offs leading to an optimized system configuration. The scope of the study has been to place major emphasis on the system elements beginning at the sensor output up through data recording and/or display on the ground. Consideration of specific user requirements and optimizing the sensor (i.e., spectral band, resolution) for those requirements has been outside the scope of this effort. As a consequence, it has been necessary to provide parametric system descriptions with data rate as the independent variable. It is possible then to relate resolution and other sensor parameters to data rate.

One of the key areas of investigation has been consideration of the feasibility of direct transmission of selected data to local users who have a requirement for real time data consumption. Such real time requirements are exemplified

by applications which include pollution detection and monitoring, damage assessment from fire, flood, storm, etc., monitoring of sea state and current, and rangeland mapping. The primary question for these local users has been feasibility of direct reception of adequate quality data via an inexpensive, simple terminal. It has been shown that this concept is feasible.

The study effort has spanned a variety of technical disciplines. Since the system is basically a high resolution satellite imaging system, the key technology areas have included on-board signal processing, modulation and channel encoding, RF link analysis, high data rate modems (100-200 Mb/s technology), high rate data handling and recording equipment, and display system techniques. Radiation has considered these diverse technologies, performed the necessary trade-off studies, and provided the desired system configurations. The study has provided definition of a system satisfying needs of both sophisticated users and local users who require low cost, simple equipment.

2.2 Study Results

The study scope and results are better understood by referring to the system block diagram given in Figure 2.2-1. The basic system elements indicated in this figure are the spacecraft, a Regional Collection Center (RCC), and a Local User Terminal (LUT). In addition a DCS capability is indicated in the block diagram.

The satellite gathers the required data via its on-board sensors and the DCS, and transmits, as commanded and programmed from the ground, to the RCC and LUT.

The Regional Collection Center receives all data generated by the spacecraft during periods of mutual visibility. This data is primarily high resolution, multi-spectral band image data which is digitally transmitted at rates on the order of 100-200 Mb/s. The function of the Regional Center then is to receive and record this information for ultimate processing and dissemination to the users. Total earth coverage can be achieved with relatively few such terminals throughout the world. For example, one properly located center in the central United States can provide coverage of most of the North American land mass exclusive of Alaska. However, there is an inherent time lag in providing processed data to the wide variety of and geographically diverse users and experimenters.

The second terminal type, the LUT, provides for the needs of a local user. This user is characterized by a requirement for less data, perhaps a single spectral band derived for a limited area, but requires near real time operation and consumption. The desired data, transmitted in a broadcast mode as programmed

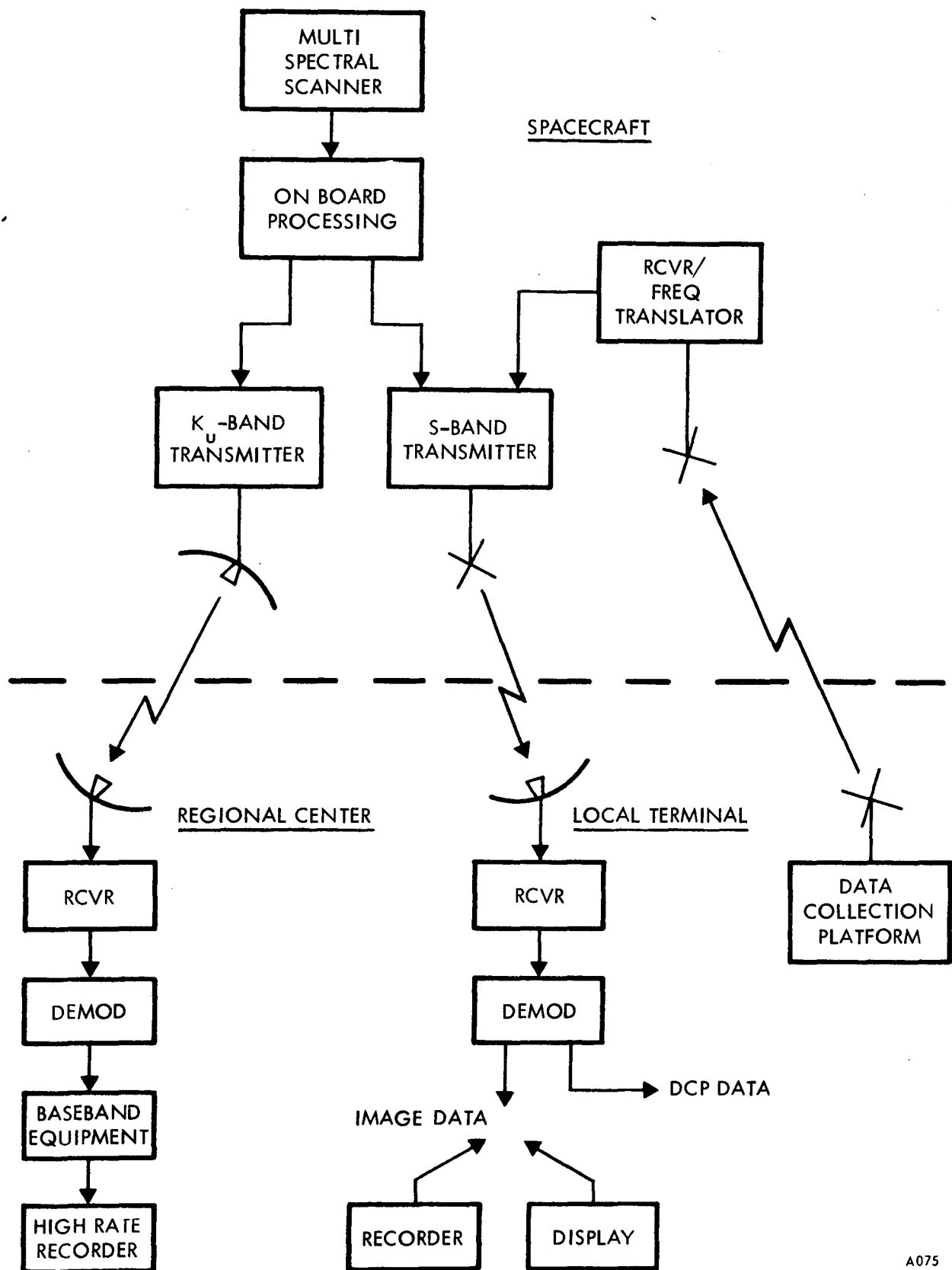


Figure 2.2-1. System Block Diagram

from the ground, can be received and hard copy image outputs provided with ground resolutions on the order of 100 meters. This very desirable capability can be achieved with nominal cost and complexity for the local users. A DCS capability, similar to that planned for ERTS-A, is also indicated and can be easily provided.

Each of the major system elements is described further in subsequent paragraphs of this summary. It was previously indicated that a variety of topics have been considered in this effort. This variety is illustrated by Figures 2.2-2 and 2.2-3 and Table 2.2-1 which are typical examples of generalized technology forecasts and technology results. Figure 2.2-2 shows state-of-the-art preamplifier noise temperatures projected for the 1975 era, while Figure 2.2-3 is a plot of attenuation due to rainfall as a function of rainfall rate at 15 GHz. This data is pertinent since the 15 GHz range is one of the candidate carrier frequencies for the RCC. Table 2.2-1 summarizes channel encoding technology by giving the coding gain realizable and relative implementation complexity for a variety of techniques. The high degree of dependence of complexity on data rate is noteworthy.

2.3 Spacecraft Summary

Figure 2.3-1 is a functional block diagram of the telecommunication systems envisioned for the Earth Observation Satellites. Maximum utilization of previously developed and proven hardware is indicated along with the two independent transmitters: Mode I for transmission to the RCC and Mode II for transmission to the LUT. The DCS capability included would be compatible with existing platforms and Receiving Site Equipment (RSE). As discussed in this report, this is probably not optimum for future systems serving a variety of users and other alternatives should be considered. While not indicated, the DCS data could easily be transmitted to the RCC with little impact on the channel capacity for MSS data.

Table 2.3-1 summarizes the spacecraft parameters which have evolved. Many variations are presented in the text of this report, especially for the Mode II system which has been described parametrically.

2.4 RCC Summary

The purpose of the Regional Collection Center is to receive, demodulate, and record high rate, high resolution image data. The functional elements required to satisfy this mission are illustrated by Figure 2.4-1. In order to maximize coverage, the system must operate to low elevation angles, nominally 5° minimum. Because of expected high data rates (50-200 Mb/s), operation will be constrained to X-Band or higher to relieve spectrum crowding. Three specific frequencies have been considered in this study, namely, 8.4, 15.25, and 21.2 GHz.

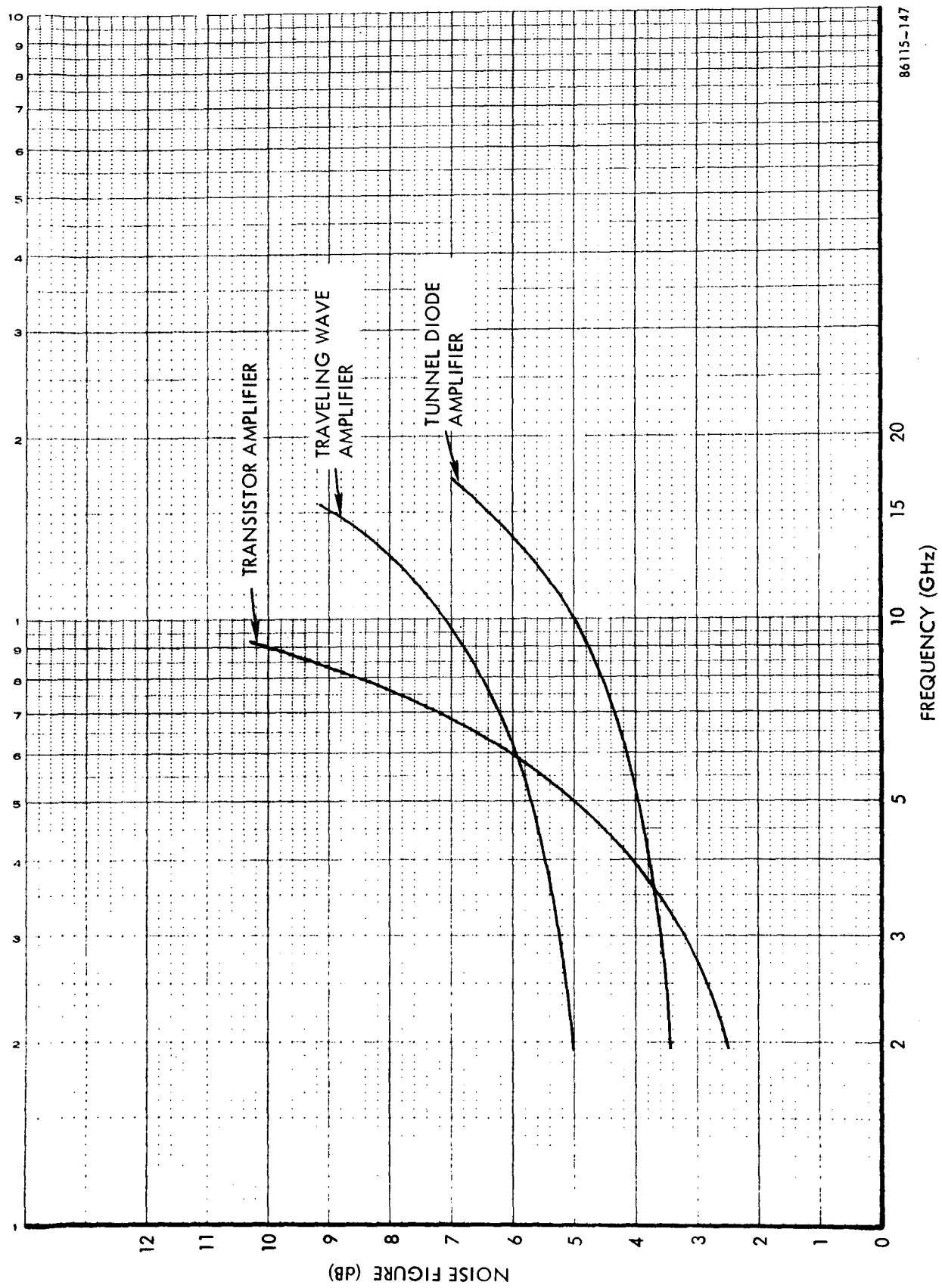


Figure 2.2-2. TWT TDA Transistor Noise Figures

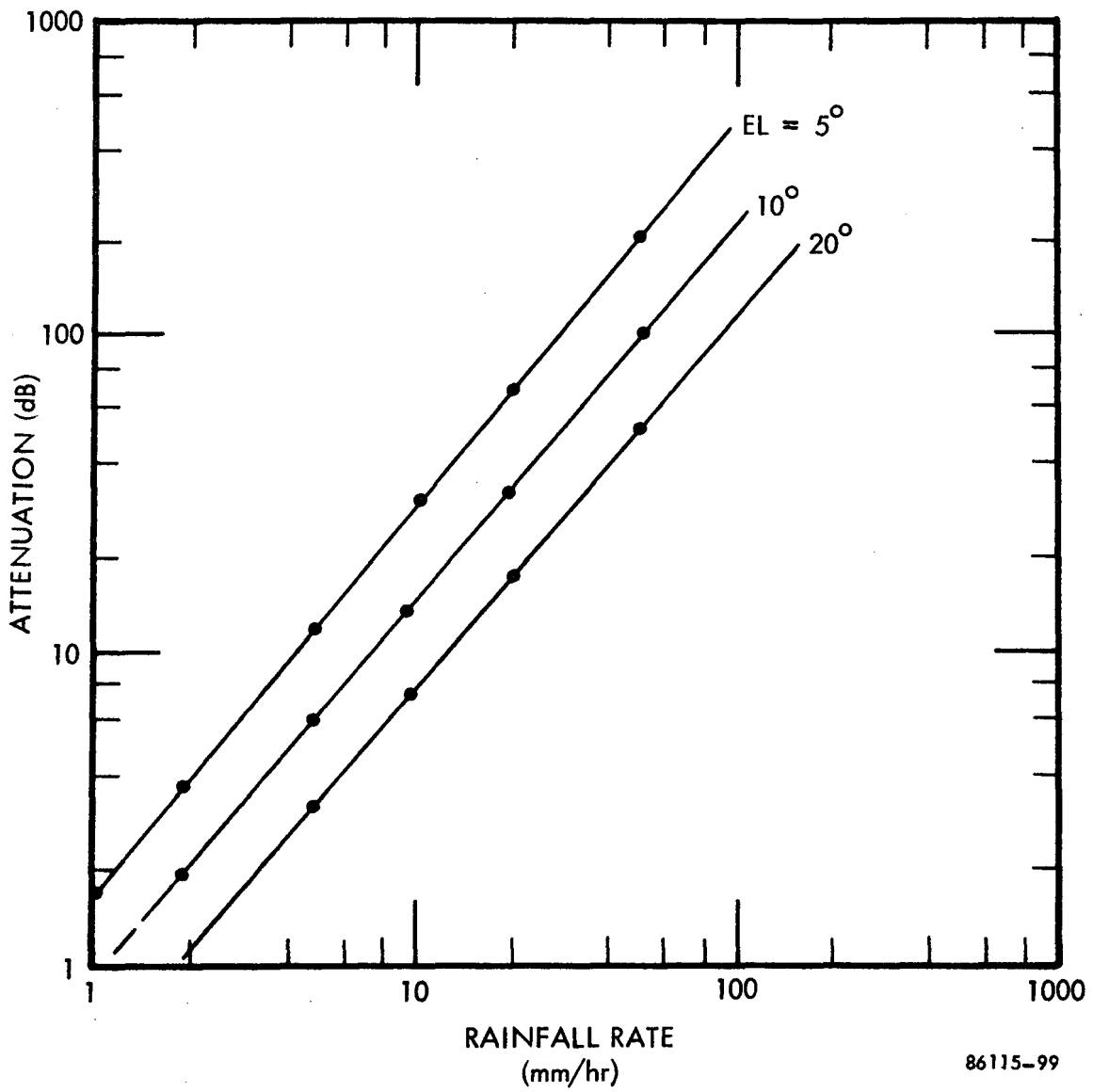
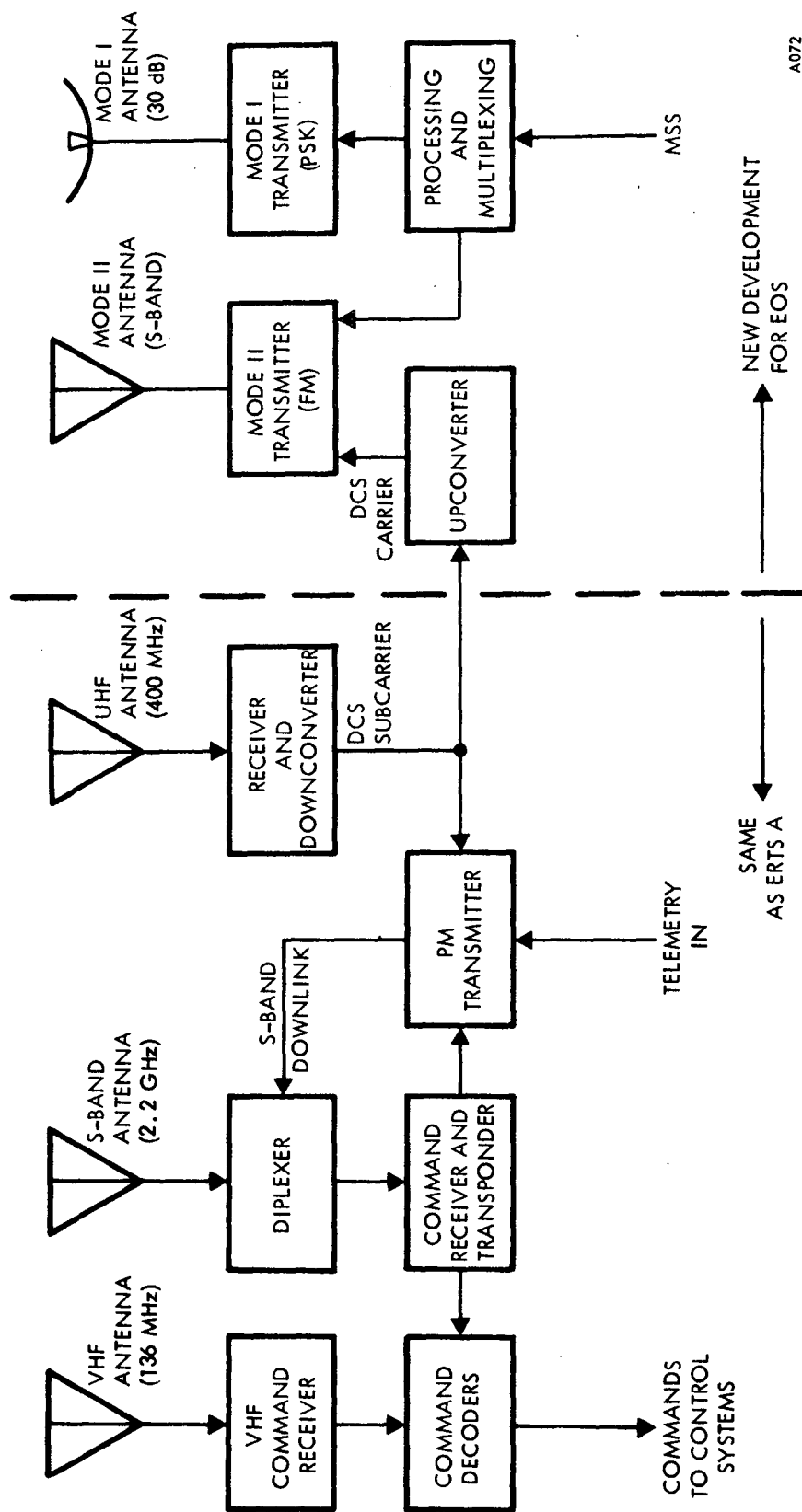


Figure 2.2-3. Rainfall Attenuation at 15 GHz (Model from CCIR)



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Figure 2.3-1. Potential EOS Communication Subsystems

Table 2.3-1. Salient Parameters of Satellite Communication System

	Mode I - RCC	Mode II - LUT
Data Source	MSS	Single Channel of MSS*
Modulation Type	PSK	Analog FM
Data Rate	100 Mb/s	100-300 KHz
Power Output	10 watts	10 watts
Carrier Frequency	15.25 GHz	S-Band
Antenna Gain	30 dB (5° -3 dB beamwidth)	-3 dB On Axis +3 dB @ ±52°
Antenna Type	Parabola or Horn	Turnstile
Pointing	Program Track	Fixed Beam
Polarization	Circular	Circular

*May also include low rate DCS data

It has been determined that the requirements can be satisfied by a system employing a high efficiency feed and 16 foot diameter parabolic antenna, uncooled parametric amplifier front end (for a 100 Mb/s data rate or less), and demodulators and processing equipment which could be implemented with low risk using present technology. A critical system element is the high rate recorder. Availability of suitable off-the-shelf equipment is very dependent upon data rate with present technology limited to around 60 Mb/s or less. However, higher rate recording is certainly feasible and several techniques are presently being developed. One of the more promising is a holographic laser recording method. It seems likely that some form of error correction coding will be required in order to ensure the goal of a 10^{-6} bit error probability. This can be done at the spacecraft or ground.

Estimated costs of the baseline 15.25 GHz, 100 Mb/s system are summarized in Table 2.4-1. Costs are given for both the first system and any

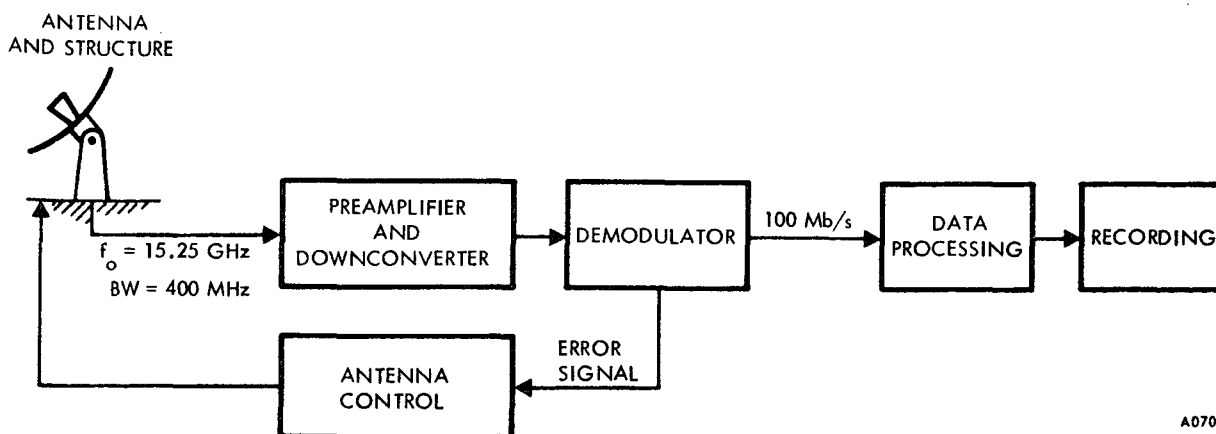


Figure 2.4-1. Regional Collection Center Functional Block Diagram

Table 2.4.1 RCC Estimated Cost for Baseline 15.25 GHz, 100 Mb/s System

	First System Cost	Recurring Cost
Antenna Feed and Microwave	65K	35K
Antenna Pedestal and Reflector	150	100
Antenna Control	220	135
Receiver	195	160
Data Processing ¹	175	50
Data Recording	200	150
Documentation	240	-
Other ²	355	220
	—	—
TOTAL	\$1,600K	\$850K

¹ Assumes PSK; Cost increases by approximately 35K for QPSK.

² Includes Program Management, System Engineering, Integration, Installation, Test, etc.

subsequent purchases. It is possible that the first system cost can be significantly reduced if appropriate development occurs on other programs. Such development is likely in the 15 GHz range, but unlikely at 21.2 GHz. One of the more significant potential variations is that of a change in frequency. Implementation at 8.4 and 21.2 GHz were considered and the cost differential to be expected was found to be less than intuitively expected. For example, an increase of less than 15% is expected if the system operation is forced to 21.2 GHz. However, the space-craft impact will be substantial, technical risk increased, and degraded performance must be accepted. Therefore it is desirable to avoid the higher frequency operation if possible.

2.5 LUT Summary

The subsystems required for the Local User Terminal are indicated by the block diagram of Figure 2.5-1. Maximum utilization should be made of existing equipments in order to minimize the cost and provide a reliable, easily maintainable system. System performance has been described parametrically in this study, the independent parameter being data rate which is directly related to LUT complexity. For example, Figure 2.5-2 is a plot of data rate versus antenna size assuming S-Band operation. The signal quality utilized for this analyses was 30 dB signal-to-noise ratio for the analog system and a 10^{-5} BEP for digital transmission. Resolution, the parameter of ultimate interest to the user, is related to data rate in Figure 2.5-3.

These results have been utilized to derive the summary found in Table 2.5-1 where performance and estimated recurring cost are given for several LUT alternatives. It is seen that good quality medium resolution image data can be successfully received and displayed by the local users on a cost effective basis.

Implementation at VHF/UHF (300 MHz, for example) is especially attractive on a cost basis since manual tracking can be utilized.

A real time capability, as would be provided by the LUT, will increase the utility of the system and allow direct participation by users who might otherwise be excluded. Because of these factors and the basic feasibility of providing the desired capability, it appears that planning should continue to include this option.

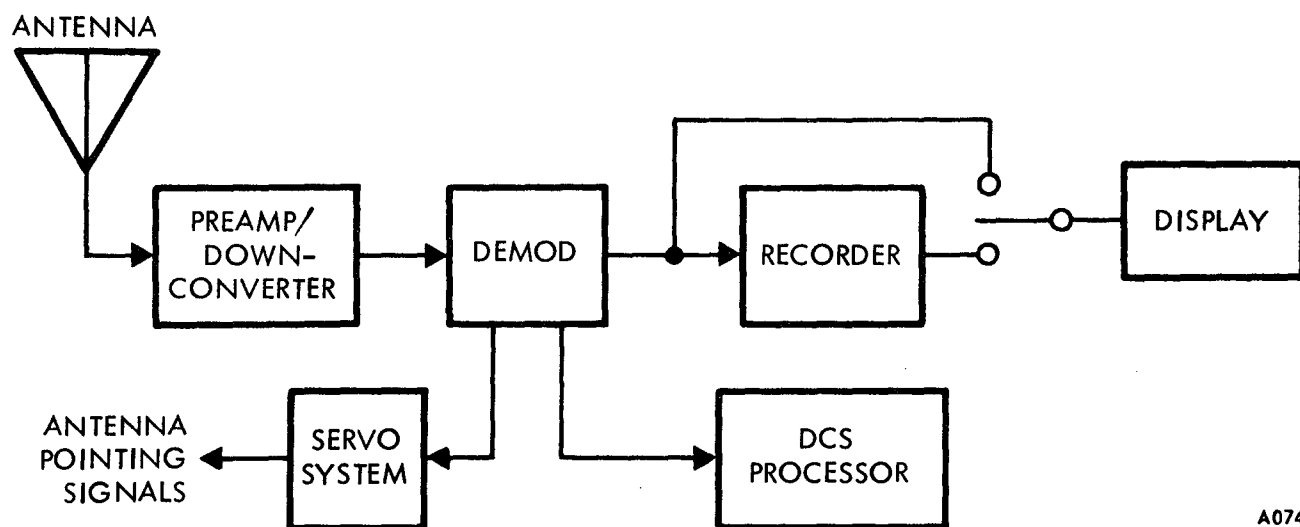


Figure 2.5-1. Functional Block Diagram for Local User Terminal

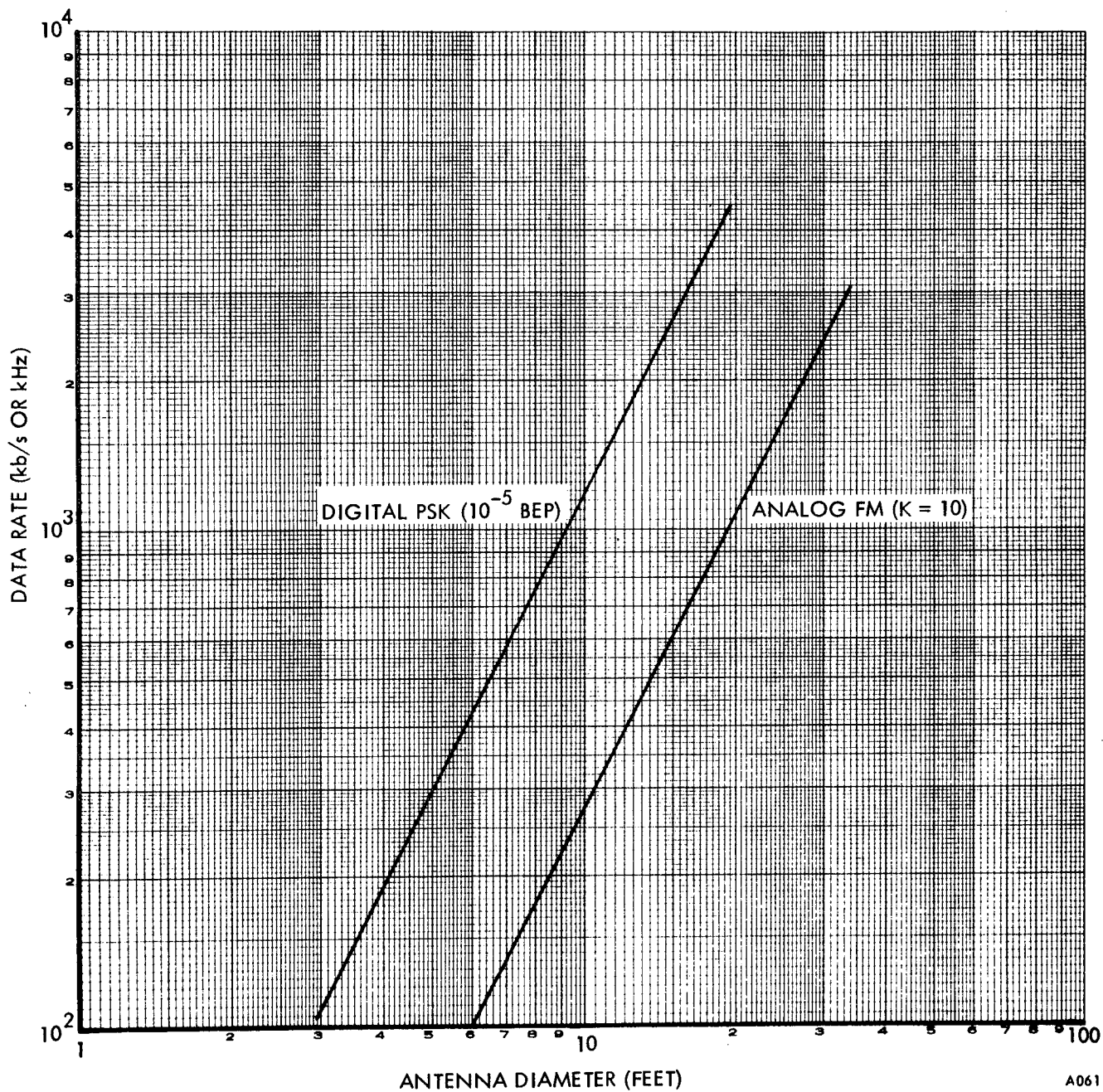


Figure 2.5-2. Information Rate for S-Band System

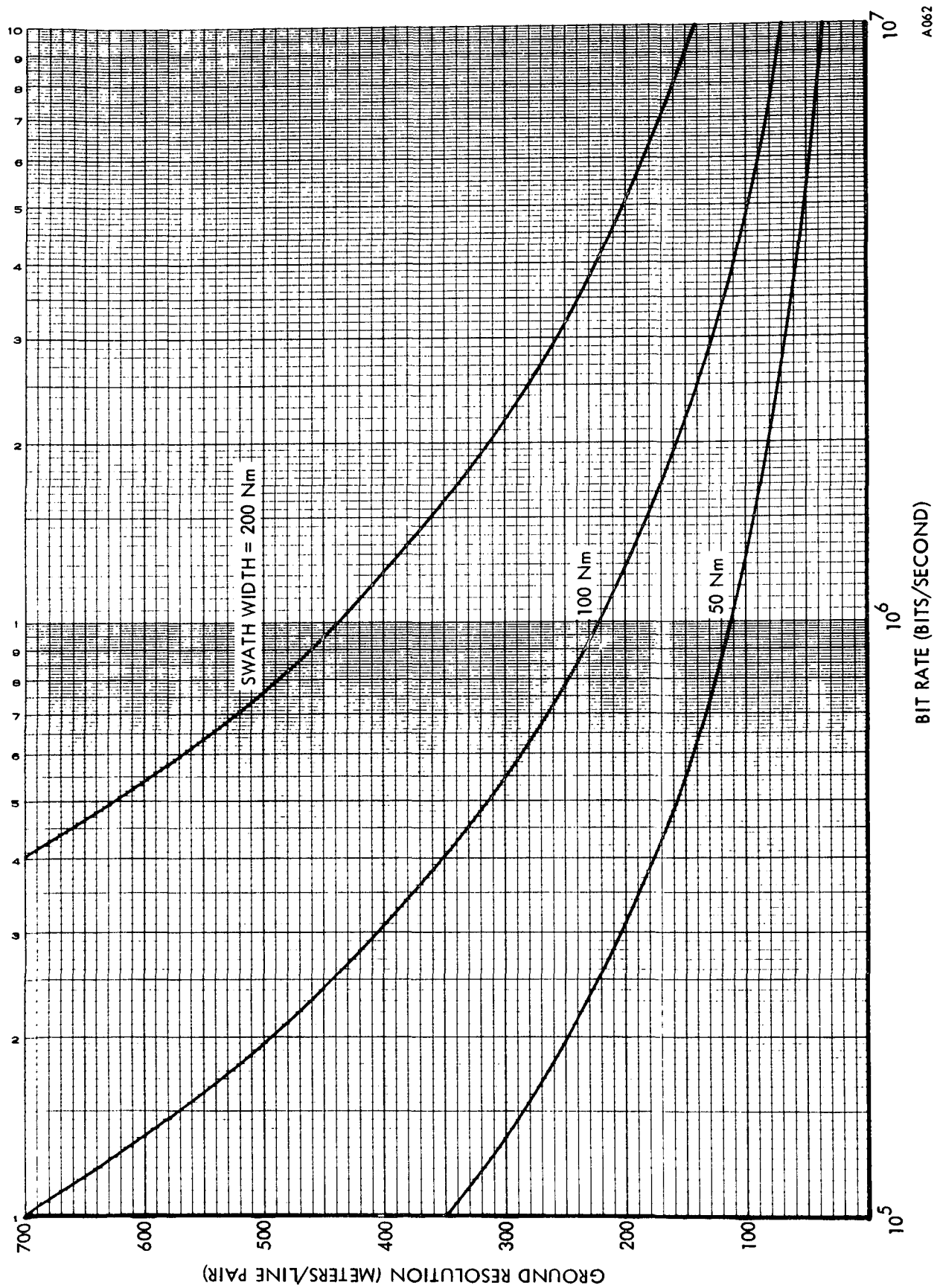


Figure 2.5-3. Ground Resolutions as a Function of Data Rate for ERTS Parameters

Table 2.5-1. Performance of Cost Summary

System Alternative Parameter	10' Dish	10' Dish w/Coding	6'Dish	6' Dish w/Coding	3' Dish	VHF/UHF
Carrier Frequency	S-Band	S-Band	S-Band	S-Band	S-Band	350 MHz
Bit Rate (Mb/s for PSK)	1.18	3.72	.43	1.36	.11	1.1
Video Bandwidth (kHz for Analog FM)	275	—	100	—	25.6	250
*Resolution (m/line-pair) Digital Transmission	205	110	340	190	675	210
Analog Transmission	140	—	250	—	485	155
Terminal Cost (\$K)	198	228	178	218	80	121

*100 mile swath width

3.0 GENERAL SYSTEM CONSIDERATIONS

To configure an optimum system, it is necessary to consider all facets of the total spacecraft-ground station interaction and how these various parameters affect the performance of the ground station. This section presents a detailed examination of the important system aspects and their relationship to specific requirements.

The orbit of the satellite imposes several requirements in terms of transmission distance, expected doppler shift, and angular coverage and angular velocities over which the ground station must operate. Additionally, the orbit sets the scan time for the sensors. Should the spacecraft utilize a high gain steerable antenna, the orbit also sets the dynamic requirements for this antenna. These effects are examined in Section 3.1 for the projected satellite orbit.

The requirements of probable users must be considered in finding the system configuration. These user requirements range in scope from the data characteristics such as spatial resolution and spectral bands to the sophistication of data processing desired. While a thorough or detailed consideration of these user aspects is beyond the scope of this study, some factors are discussed in Section 3.2.

The characteristics of the sensors employed in the program have a tremendous impact on the system configuration. One major area concerned is the transmission link, since the data rate transmitted sets the requirements for the effective radiated power (ERP) from the satellite and the ground station sensitivity, i.e., gain to system noise temperature ratio (G/T_s). These parameters cannot be allocated until the total requirement is known. Another area of great importance is the structure of the sensor output data (e.g., one sensor at 100 MBPS versus 5 sensors at 20 MBPS each). This sensor data structure determines which methods of coding, recording, processing and displaying are feasible and which are not. Hence, Section 3.3 is devoted to a description of the sensors scheduled for ERTS A and B, and projects potential successors to these, operating at output data rates of 100-200 MBPS.

The transmission link can be designed only by careful consideration of many parameters. Foremost of these parameters is selection of a suitable frequency, based upon available components, bandwidth required (data rate), immunity from interference, performance of available components, and atmospheric effects. Once a frequency is selected (or, more ideally, as an aid in selection of the frequency) link budgets must be established such that allocations of antenna gains, transmitter power, and receiver sensitivity can be made. These aspects of the system configuration are treated in Section 3.4.

The orbital parameters of a satellite have a tremendous impact on the requirements of a ground station. Once the orbit is defined, these parameters can be calculated and the associated requirements of the ground station can be specifically stated. The specific orbit parameters assumed are those projected for ERTS A as given in Table 3.1-1.

Some of the important geometrical considerations are illustrated in Figure 3.1-1. One of these is range from the satellite to the ground station, which is a function of the elevation angle of the antenna. This variation in range is plotted in Figure 3.1-2. The maximum range is 1640 NM, corresponding to the specified minimum elevation angle of five degrees. Another relationship is the variation in the angle α , the angle between nadir and the direction to the ground station, with ground station elevation angle. This is shown in Figure 3.1-3. The maximum value of α is just over 60 degrees (corresponding to $EL = 5^\circ$), which means that a steerable antenna on the satellite will be required to move within a cone of 120° .

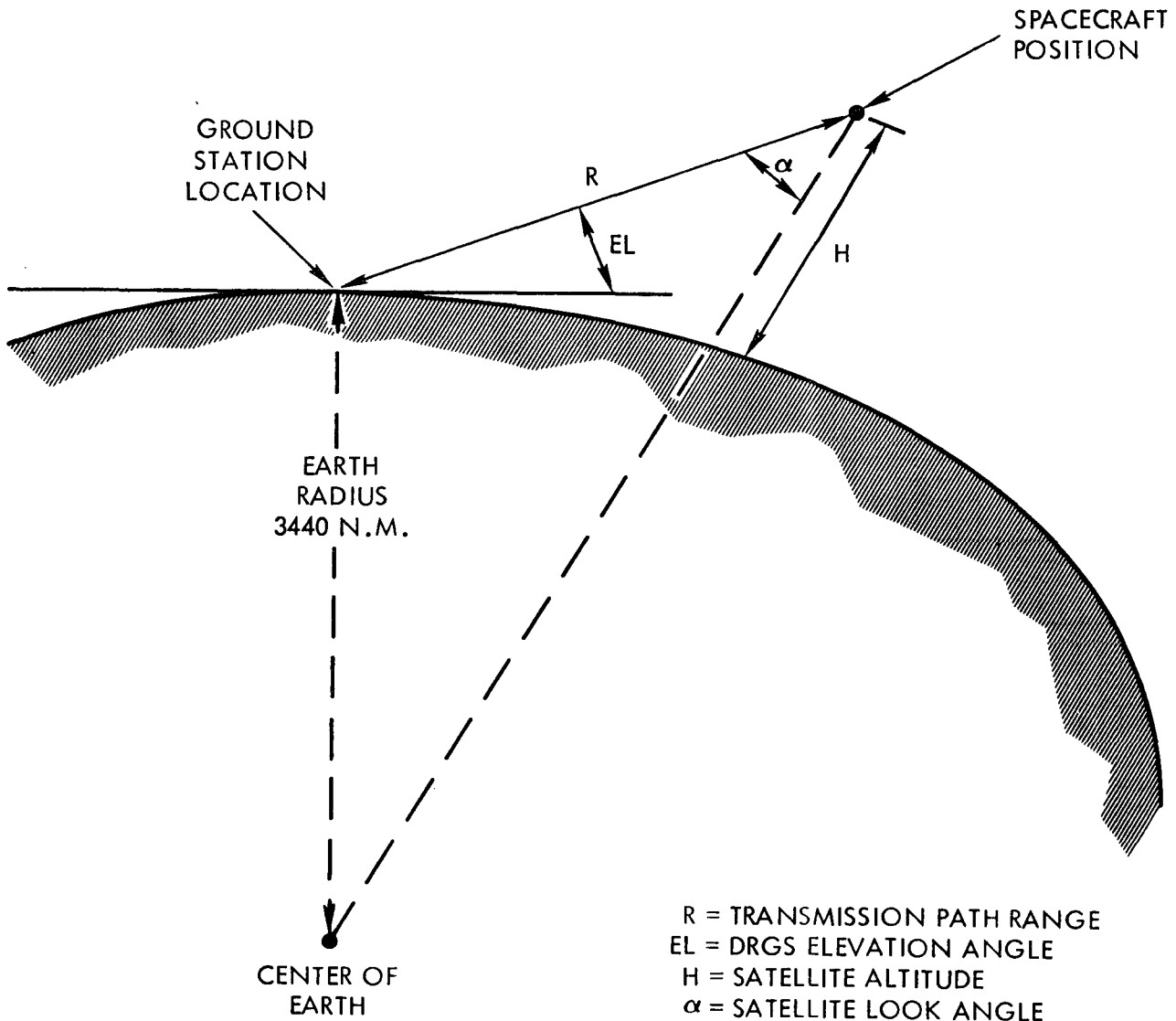


Figure 3.1-1. Geometrical Considerations

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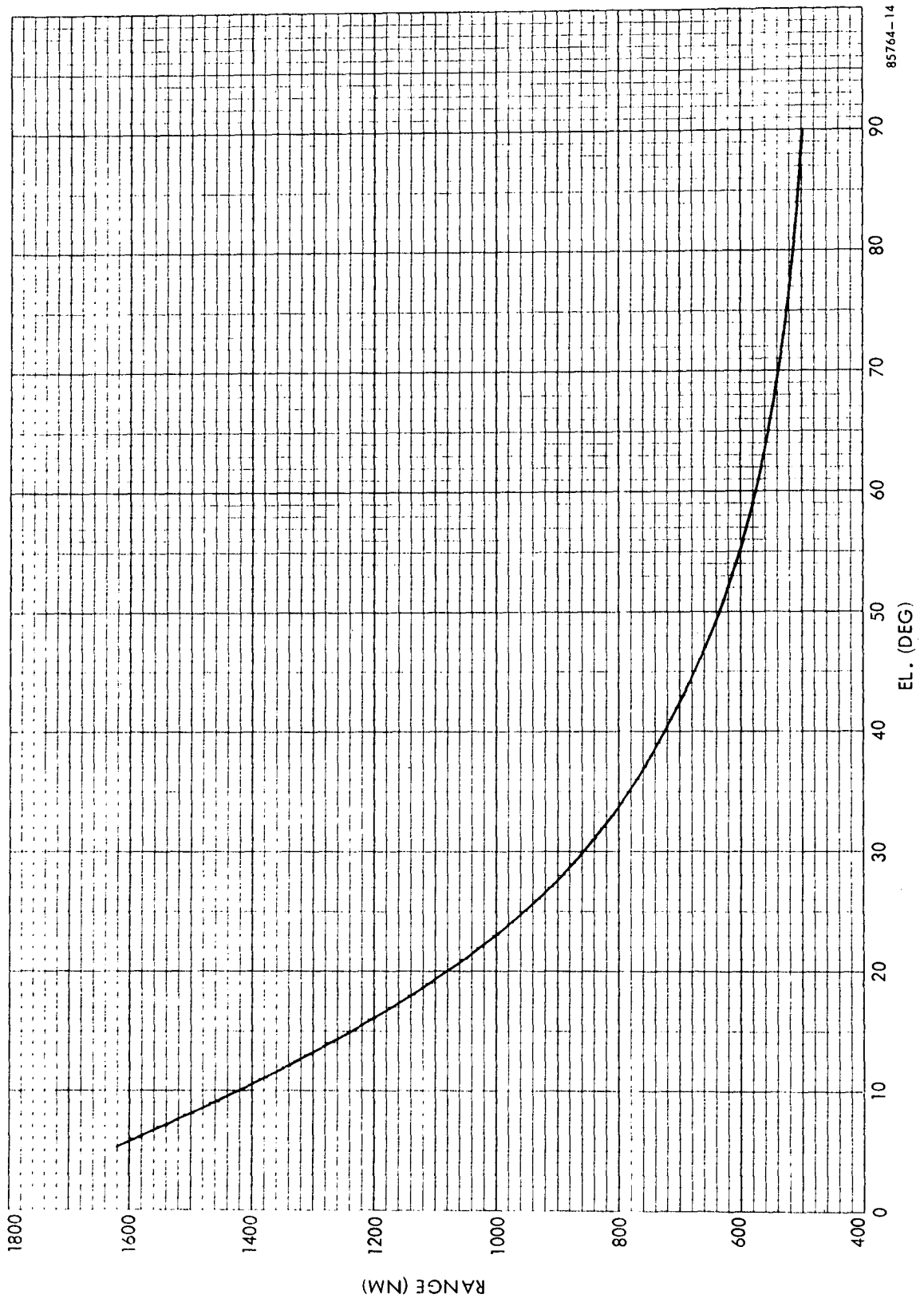


Figure 3.1-2. Transmission Link Range as a Function of DRGS Elevation Angle.

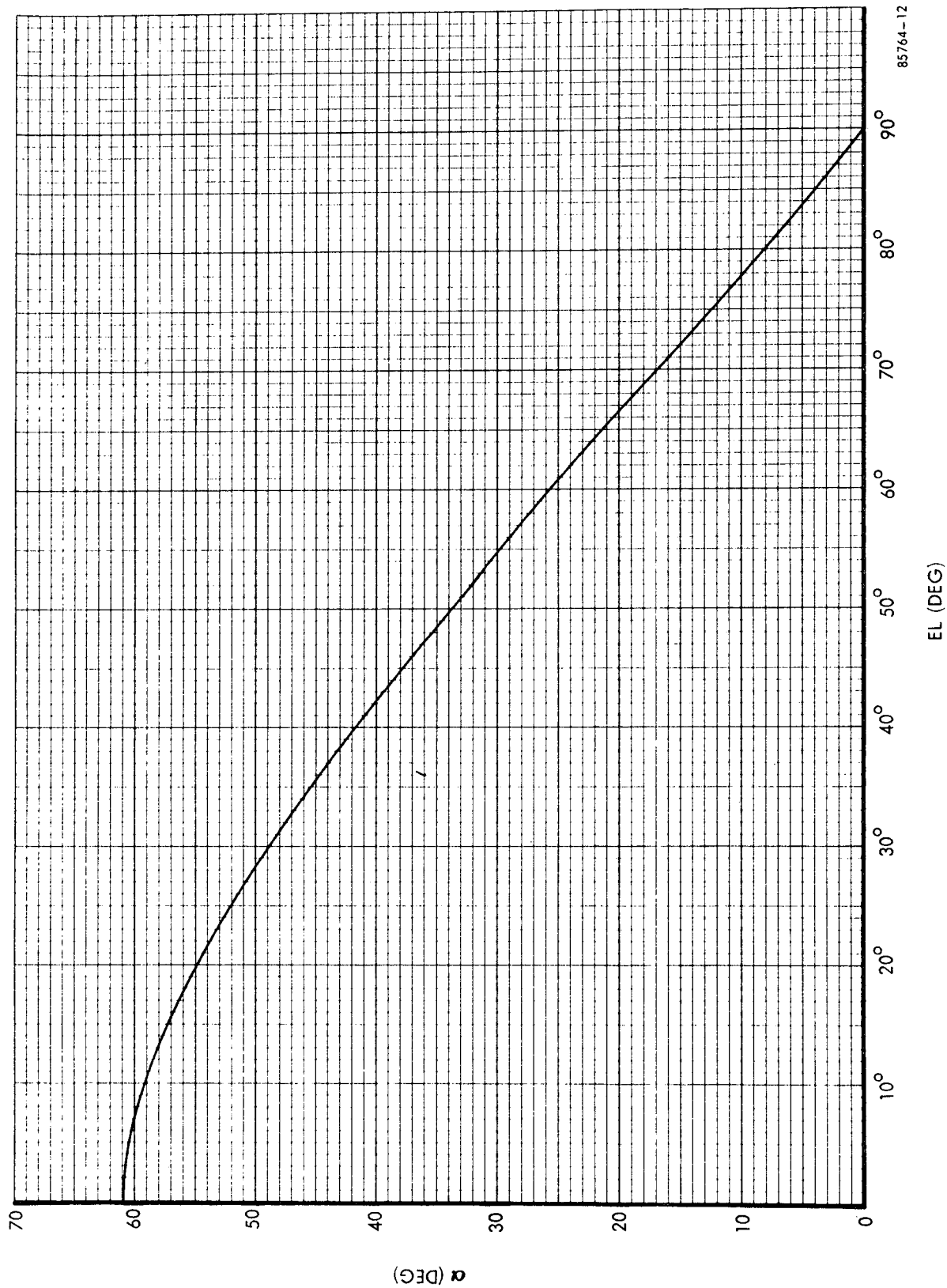


Figure 3.1-2. Spacecraft Look Angle (α) as a Function of DRGS Elevation Angle.

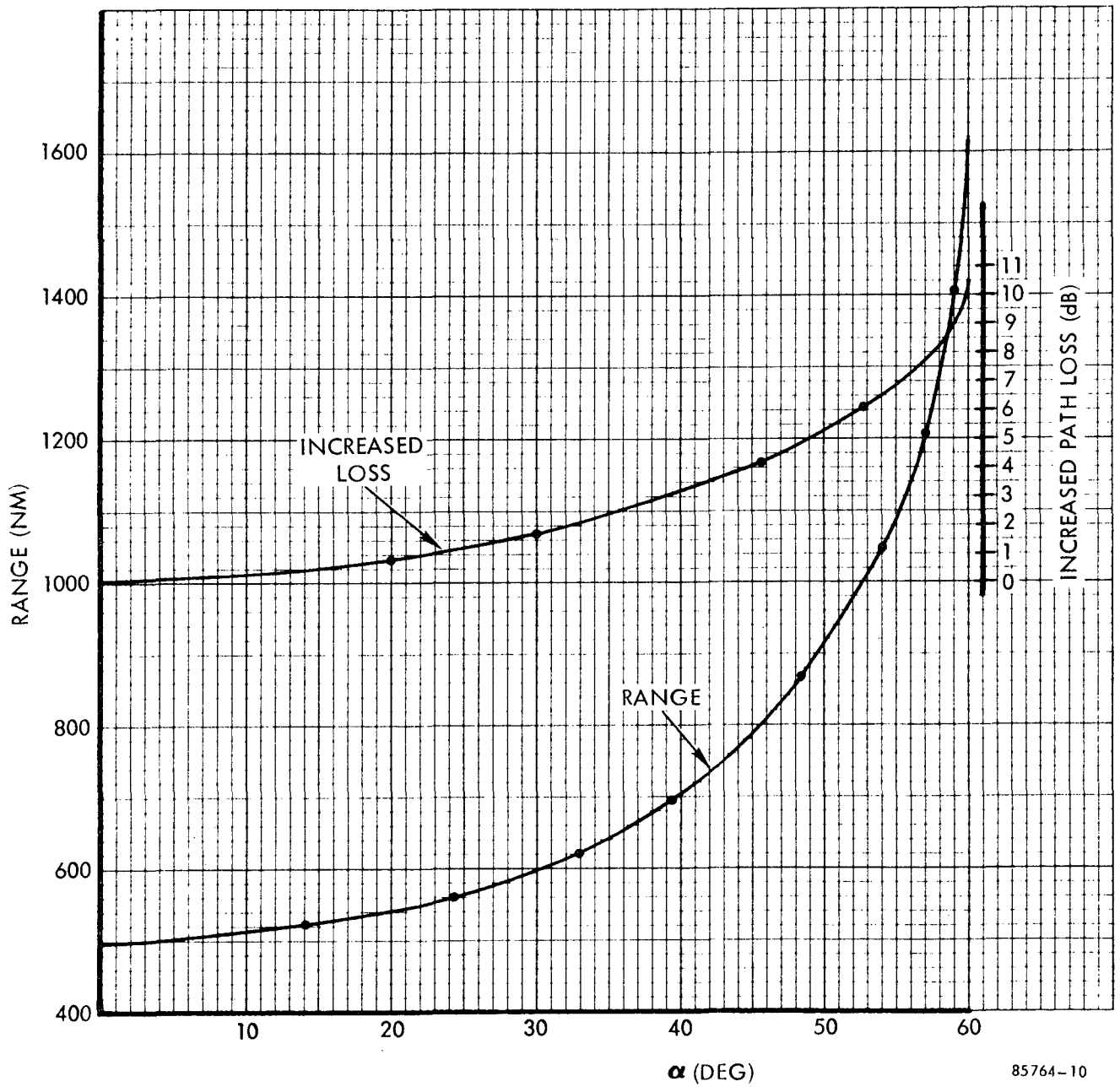
Table 3.1-1. Orbit Parameters for ERTS A*

Altitude	492.35 NM
Ellipticity	0 (circular)
Inclination	99.088 Deg.
Period	6,196 Sec.
Time of Ascending Node	21:30
Coverage Cycle Duration	18 Days (251 Revs)
Distance Between Adjacent Ground Tracks	86.06 NM
Ground Velocity	3.5 NM/Sec
<ul style="list-style-type: none"> • Daily Sub-Satellite Swaths Sidelap by Approx. 10% (at Equator) • Sub-Satellite Swaths Coincide by ± 10 Mi on Successive Coverage Cycles 	

*Source: "Earth Resources Technology Satellite (ERTS) System Design Review" 22, 23, 24 September 1970, General Electric.

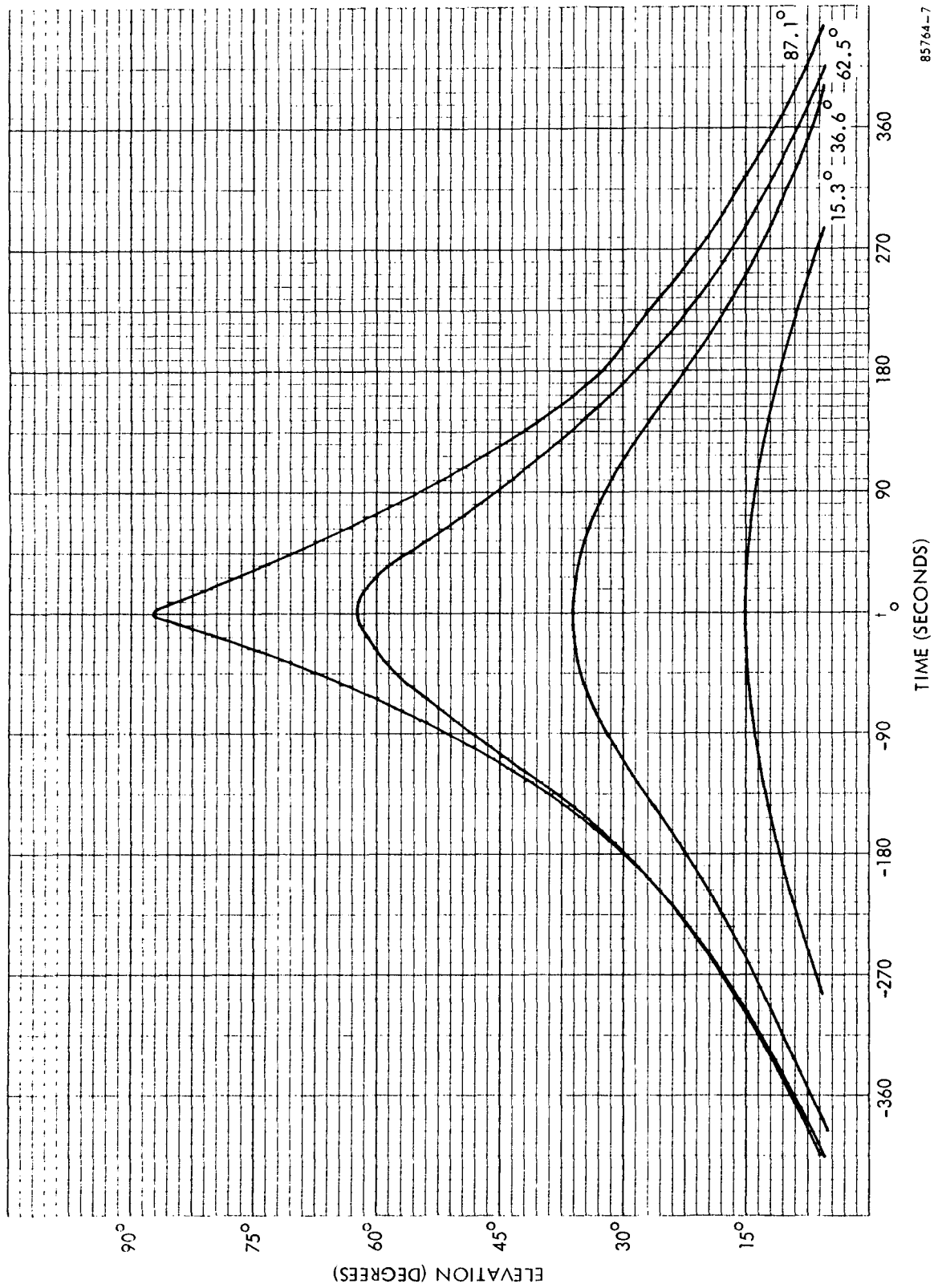
From the above curves, it is possible to express the variation in range as a function of the angle α . This is shown in Figure 3.1-4. Since the free space transmission loss varies as a specific function of range (independent of the frequency used) the variation in this transmission link signal attenuation can also be plotted as a function of α . This variation is also shown in Figure 3.1-4. If a fixed antenna is used on the spacecraft it would be desirable for the antenna gain pattern to compensate for the variation in transmission link attenuation such that the signal strength at the ground is independent of the relative position of the satellite. This problem is discussed in depth in Section 4.2.3.1.

Another category of curves which have been generated concern the pointing dynamics associated with ground antenna. An elevation-over-azimuth axis system has been assumed and a latitude of 40 degrees north. The elevation motion, elevation velocity, azimuth motion and azimuth velocity have been plotted as functions of time in Figures 3.1-5 through 3.1-8 respectively. These curves can be easily calculated for any desired latitude and show that the azimuth velocity increase drastically as the satellite orbit approaches a pass requiring high



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Figure 3.1-4. Variation in Range with Spacecraft Look Angle.



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Figure 3.1-5. Elevation Angle Motion

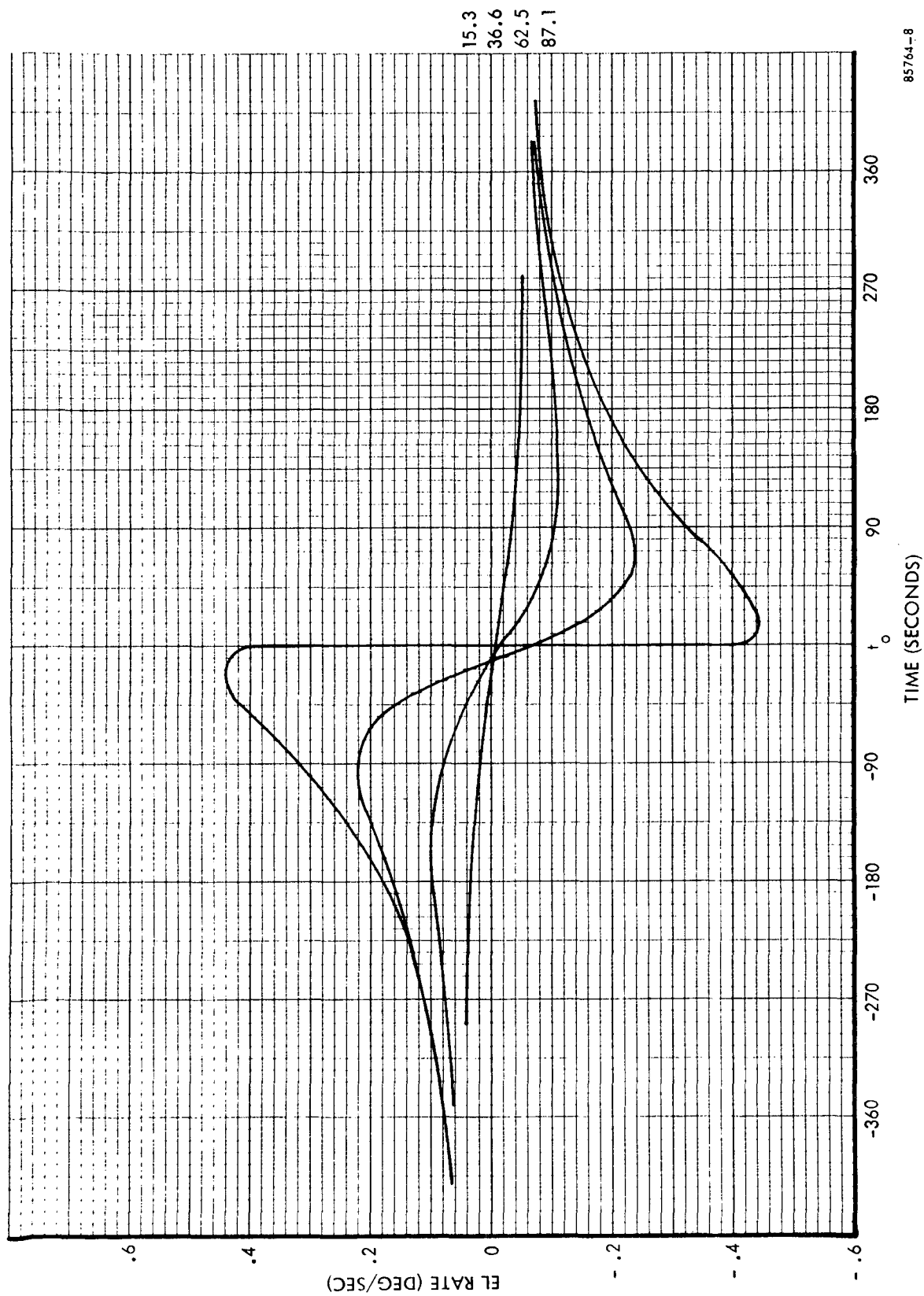
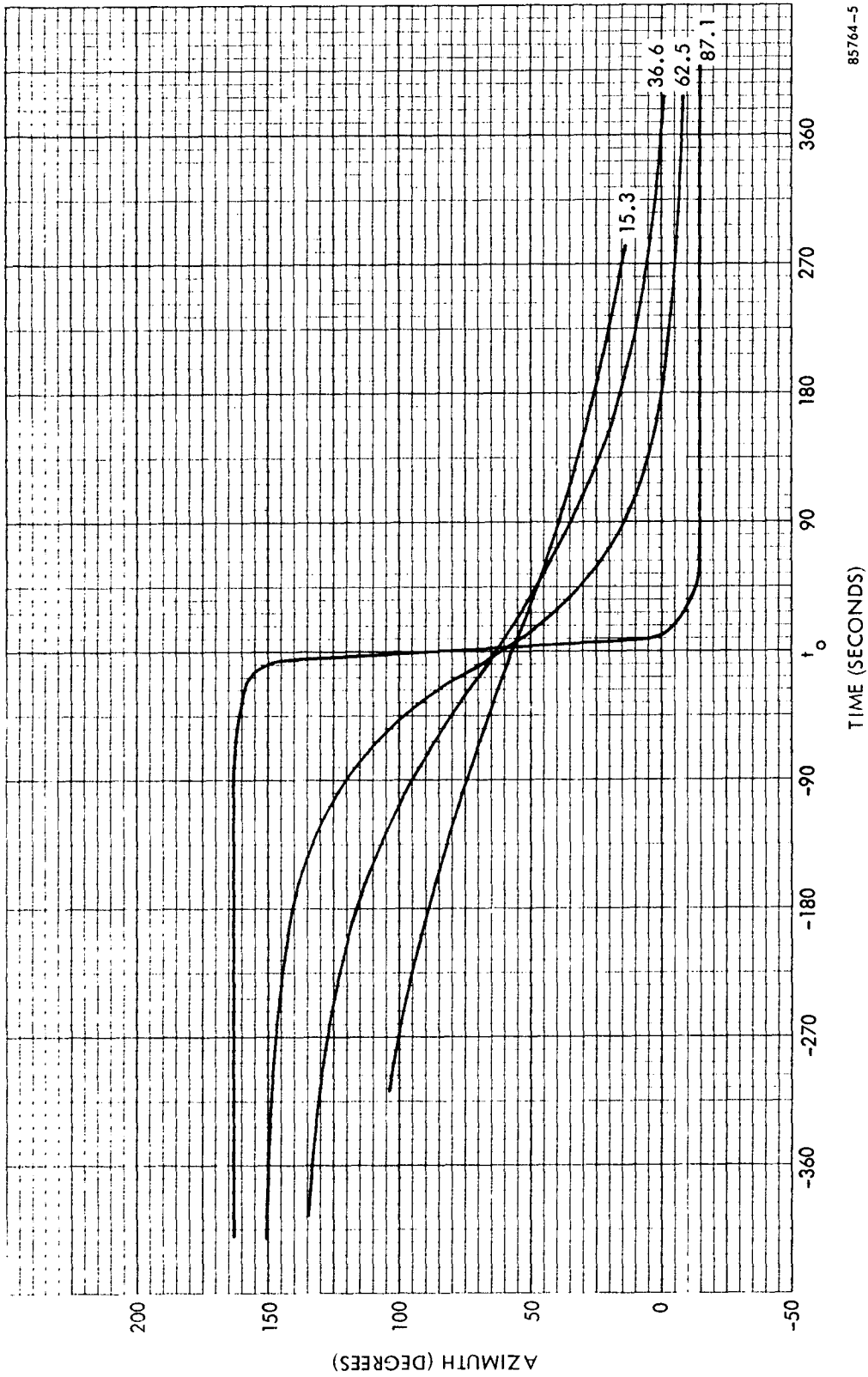
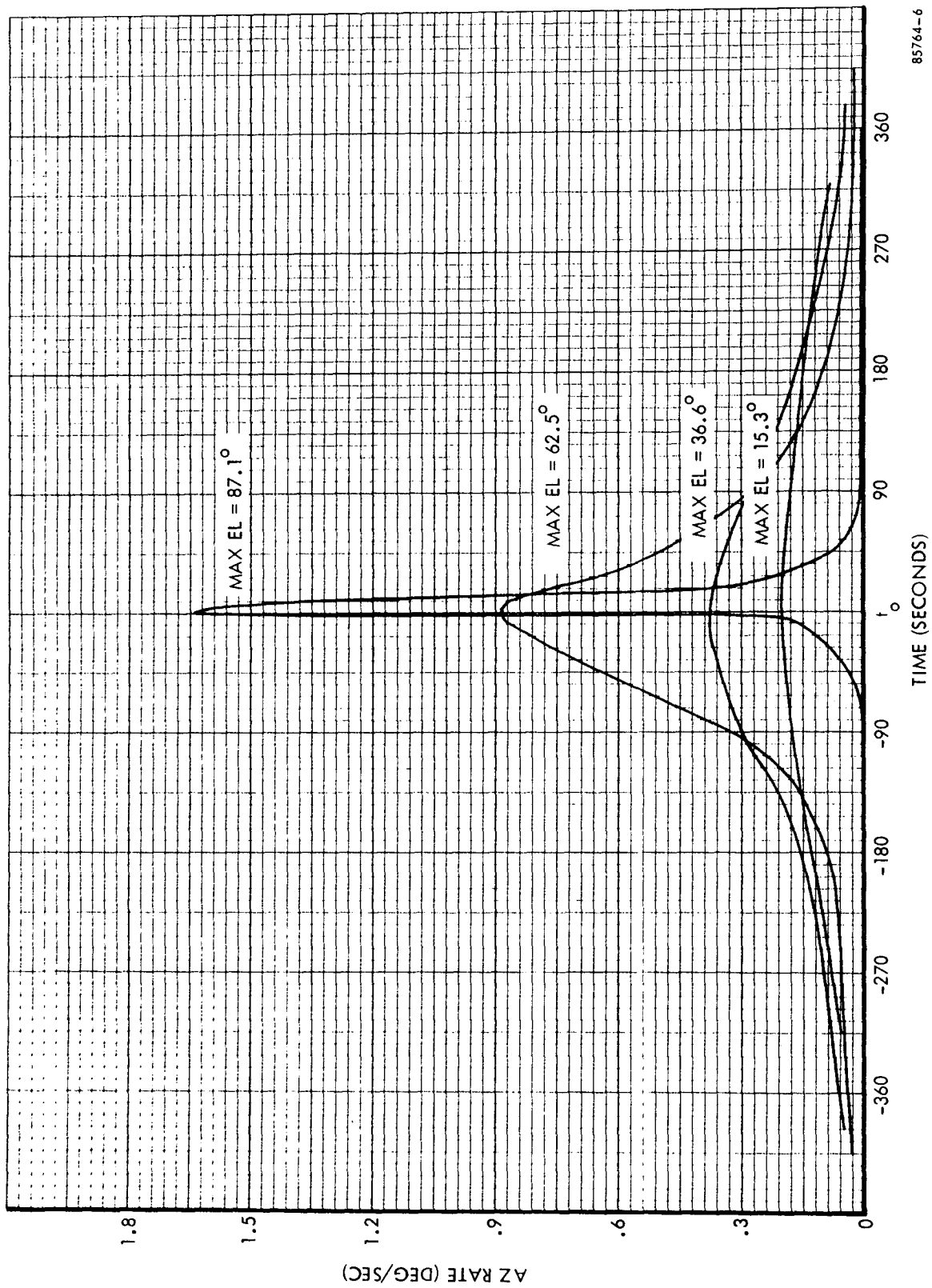


Figure 3.1-6. Elevation Angle Velocity



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Figure 3.1-7. Azimuth Angle Motion.



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Figure 3.1-8. Azimuth Angle Velocity

maximum elevation angles. In fact, if the satellite pass should go directly overhead (at the antenna "keyhole") the required azimuth velocity would be infinite. This is not a major problem, since such a small percentage of passes achieve the high elevation angle required to produce the excessive azimuth velocities. This is shown in Figure 3.1-9 which gives the percentage of passes falling below any maximum elevation angle. The lower cost of AZ-EL structures, compared to X-Y mounts, usually override the small amount of loss information due to breaking track caused by the high velocity. However, recent design advances by Radiation Systems Division have produced low cost X-Y structure approaches applicable to the Local User Terminal. With the relatively high minimum elevation angles for this situation, low dynamics ($1^\circ/\text{sec}$, $.1^\circ/\text{sec}^2$) are satisfactory.

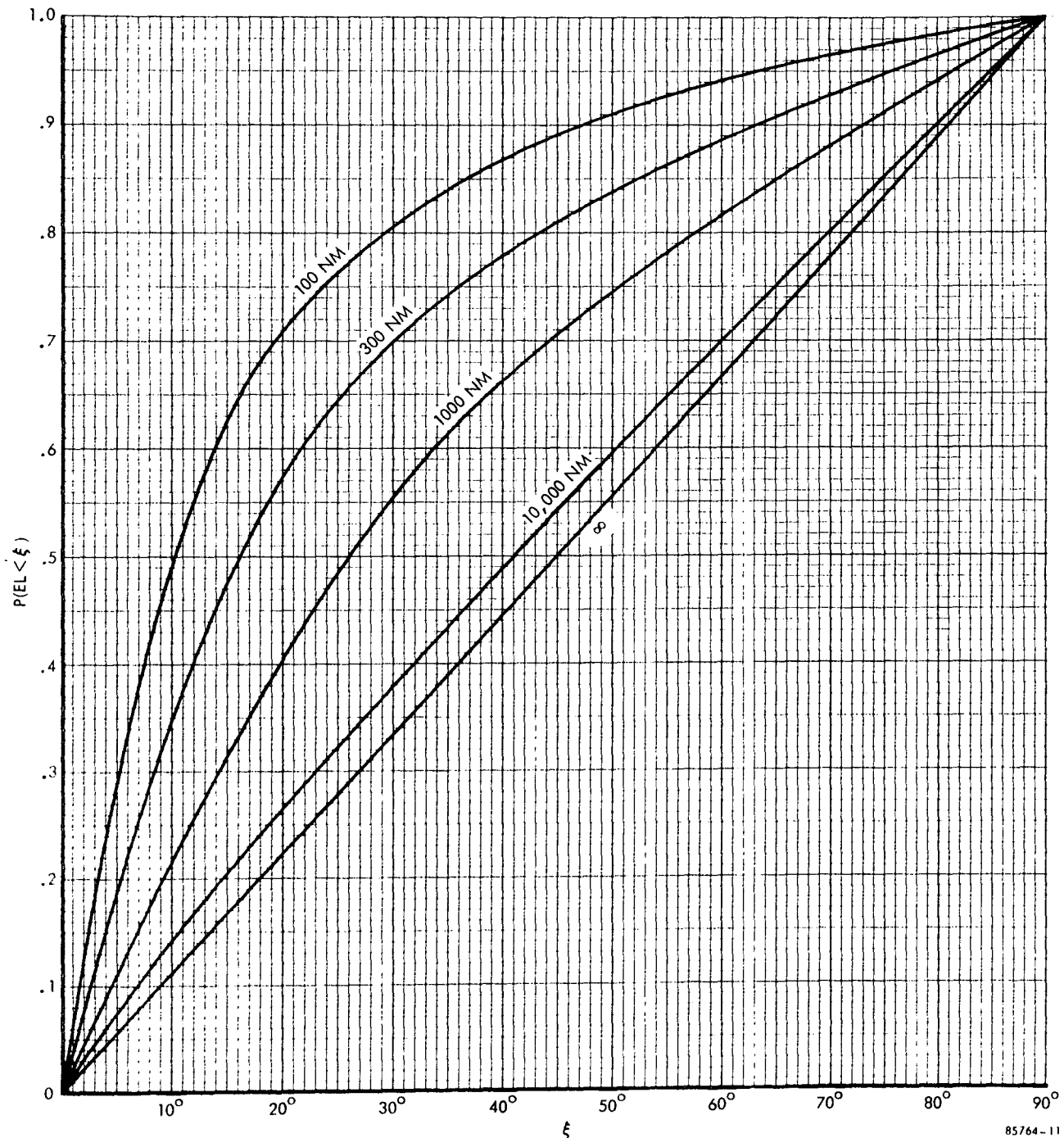


Figure 3.1-9. Probability of $EL \leq \xi$

The probabilistic model assumed in Figure 3.1-9 is not entirely realistic for a stable orbit such as ERTS. In fact, only 1 pass out of each 72 should produce a condition wherein a nominal 84-85° elevation angle is exceeded. Therefore, even for an AZ-EL structure good performance on a near continuous basis is achieved with relatively low dynamics. A design accommodating 2°/sec velocity and .1°/sec² acceleration on the azimuth axis should provide the necessary performance. Lesser dynamics are required on the elevation axis, on the order of .5°/sec velocity and .0025°/sec² acceleration.

The DRGS axes accelerations have not been shown here but can easily be estimated from the velocity-time plots or calculated on the computer. Similarly, the rates associated with a steerable antenna on the spacecraft have not been calculated since these depend upon the particular axis arrangement chosen. It is a simple matter to compute these if so required.

One other feature that must be considered is the doppler frequency shift the receiving system must accommodate. This is a function of the satellite orbit and the carrier frequency used. A normalized plot (Hz doppler/GHz of carrier) is shown in Figure 3.1-10 for this orbit under various maximum elevation angle passes.

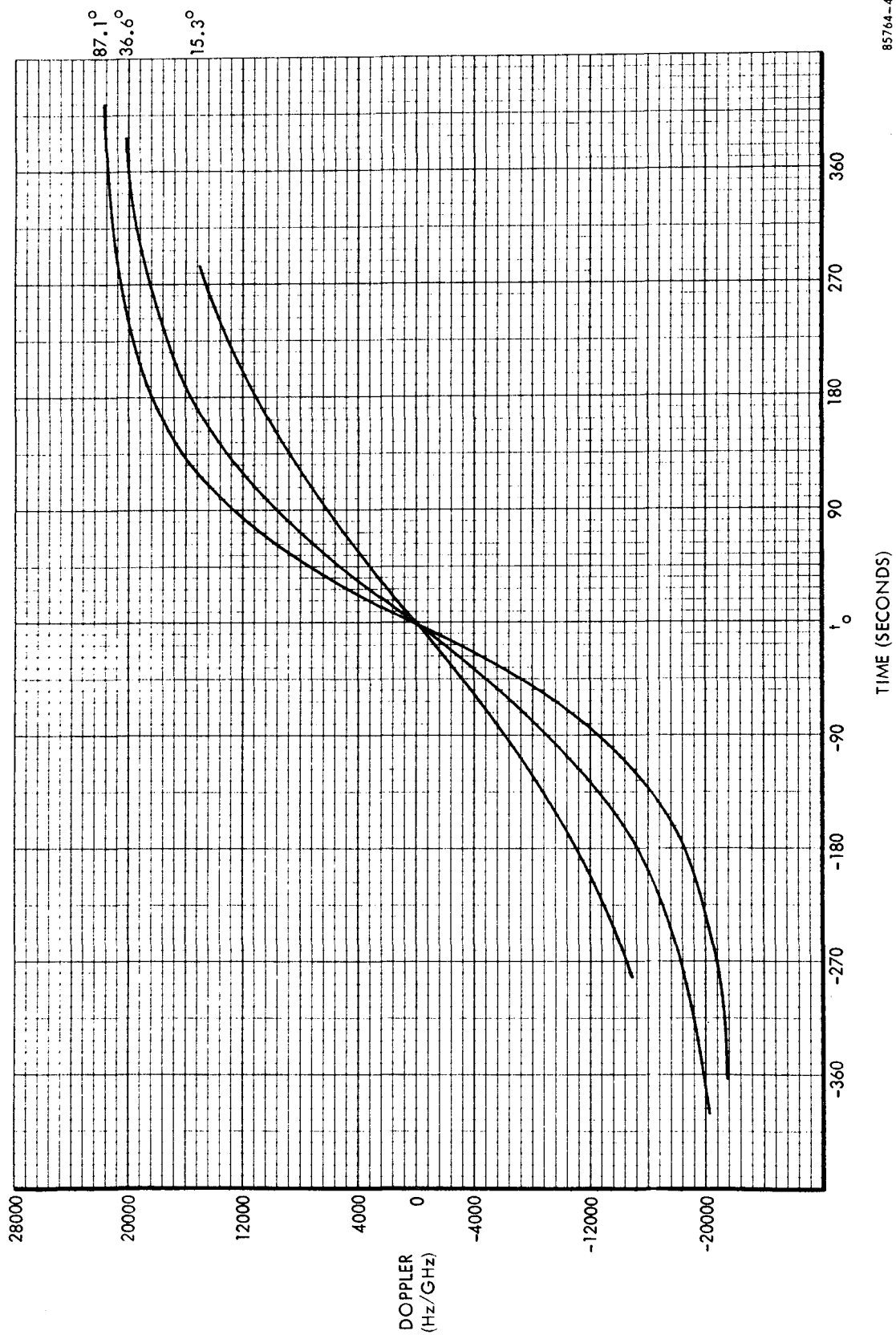
Still other important factors related to the satellite orbit are the coverage and contact times available to a given user terminal. Contact time, the period of satellite visibility to the ground station, is plotted in Figure 3.1-11 for several minimum elevation angles. Coverage can be ascertained from Figure 3.1-12 which shows the relationship of elevation angle to ground distance between the ground terminal and satellite subpoint. This information is important in determining the desirable minimum elevation angle for local users.

3.2 User Considerations

The requirements of potential users of data from operational earth resource monitoring systems are extremely diverse. As a consequence, a detailed cataloging of these requirements is beyond the scope of this study and no attempt has been made to present a comprehensive list of user characteristics or needs. Nevertheless, some attention must be given to these requirements to insure the utility of system configurations recommended by the study. A few such user considerations are provided in this section.

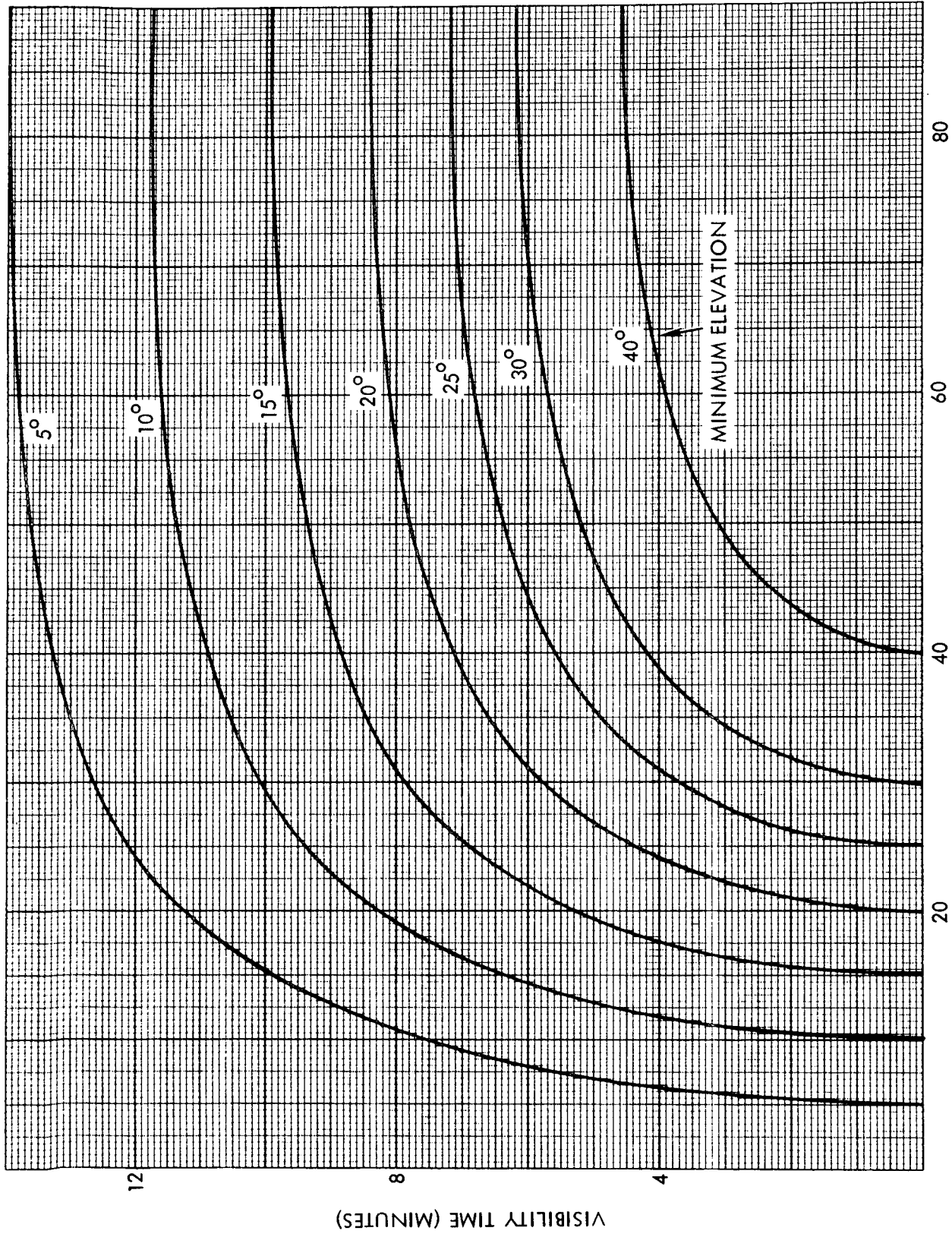
3.2.1 General Considerations

The ground stations planned for use with future Earth Observation Satellites must be user-oriented in several respects. First, local user terminals must be sufficiently simple that users can operate it with little difficulty. This must be so because such users will be mainly interested in applications of the



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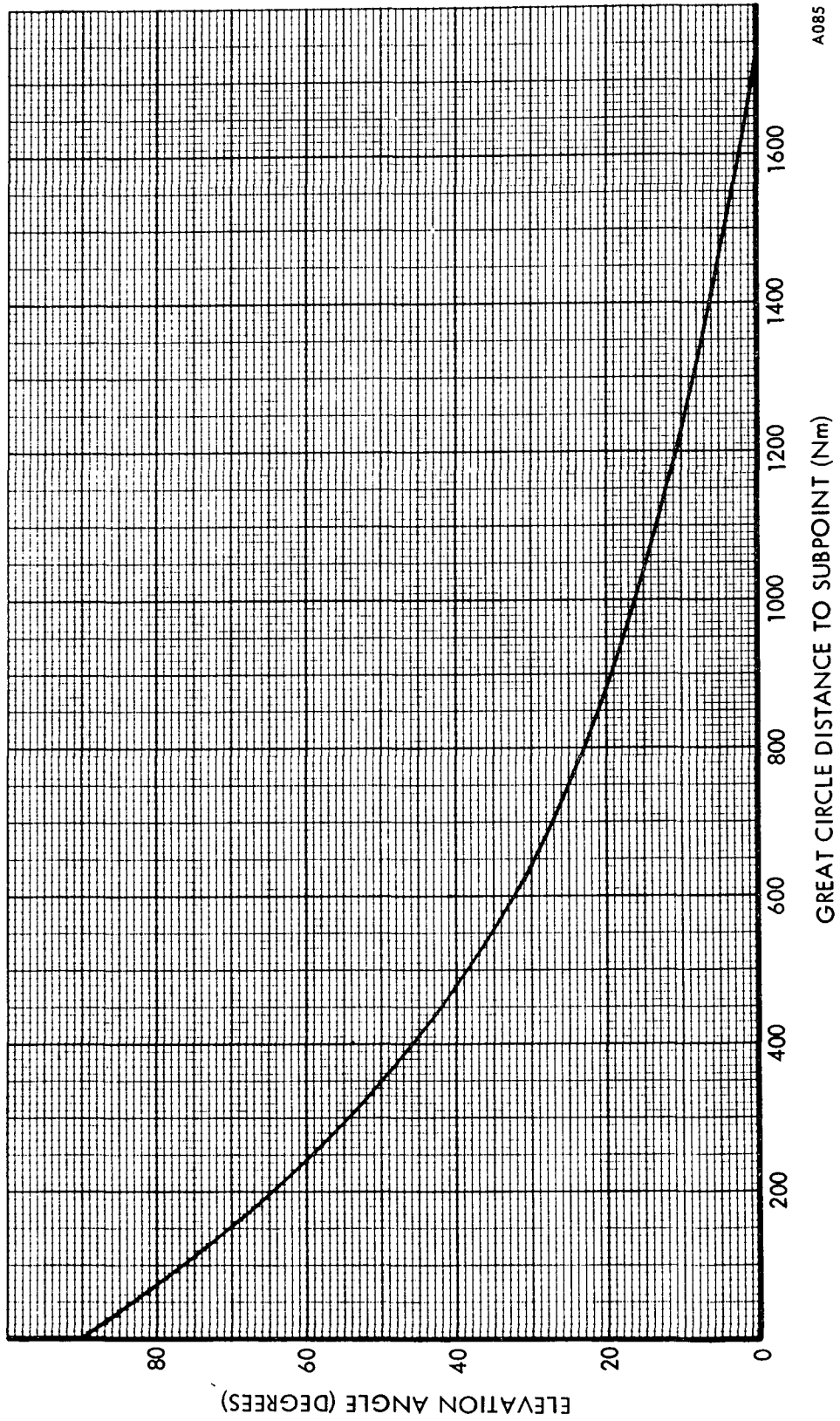
Figure 3.1-10. Normalized Doppler Shift for the ERTS Orbit



PEAK ELEVATION OF PASS (DEGREES)

Figure 3.1-11. Time Spent Above Minimum Elevation

A086



A085

Figure 3.1-12. Elevation Angle versus Distance from Ground Station to Satellite Subpoint (492 Nm Orbit)

received data, and not in operating complex ground station equipment. Secondly, it must be flexible so that a given user can select that capability needed, and not be burdened with excess equipment and costs; as for example with an overly complex display. This must be so to allow the maximum number of users and, hence, prorate the satellite costs as far as possible.

This concept of prorating the satellite costs has a "positive-feedback" effect on the system configuration to a certain extent. The sequence of actions-reactions is as follows:

- a. Lowering costs allows more users to participate.
- b. More users cause the prorated satellite costs to be lowered.
- c. This allows more total cost for the satellite and allows more on-board processing.
- d. More on-board processing allows lower costs.
- e. Etc.

Obviously, this can be logically carried only so far until a point of diminishing returns is reached. However, not to consider system tradeoffs of this type may result in a nonoptimum system.

Another consideration is the quality of data as determined by the transmission link (i.e., not as set by the sensor resolution). A bit error rate of less than 1 in 10^6 has been utilized as a baseline study parameter for digital links and a signal to noise ratio of 30 dB for analog links. An assessment of the effects of both higher and lower quality data has been made.

3.2.2 Quantity of Data

The quantity of data involved must be considered in two respects. These two are: (1) how much data is available, and (2) how much data is desired.

Quantity Available

This is dictated by the orbit and by the specified sensor coverage frame area. The parameters established by the satellite orbit have been illustrated in Figure 3.2.2 where a Mercator projection of the United States has been shown with circles of coverage for ground station elevation angles above 5° , 10° , and 20° . This demonstrates that a user located at a particular point can obtain information from distances far removed from his physical location. Another consideration

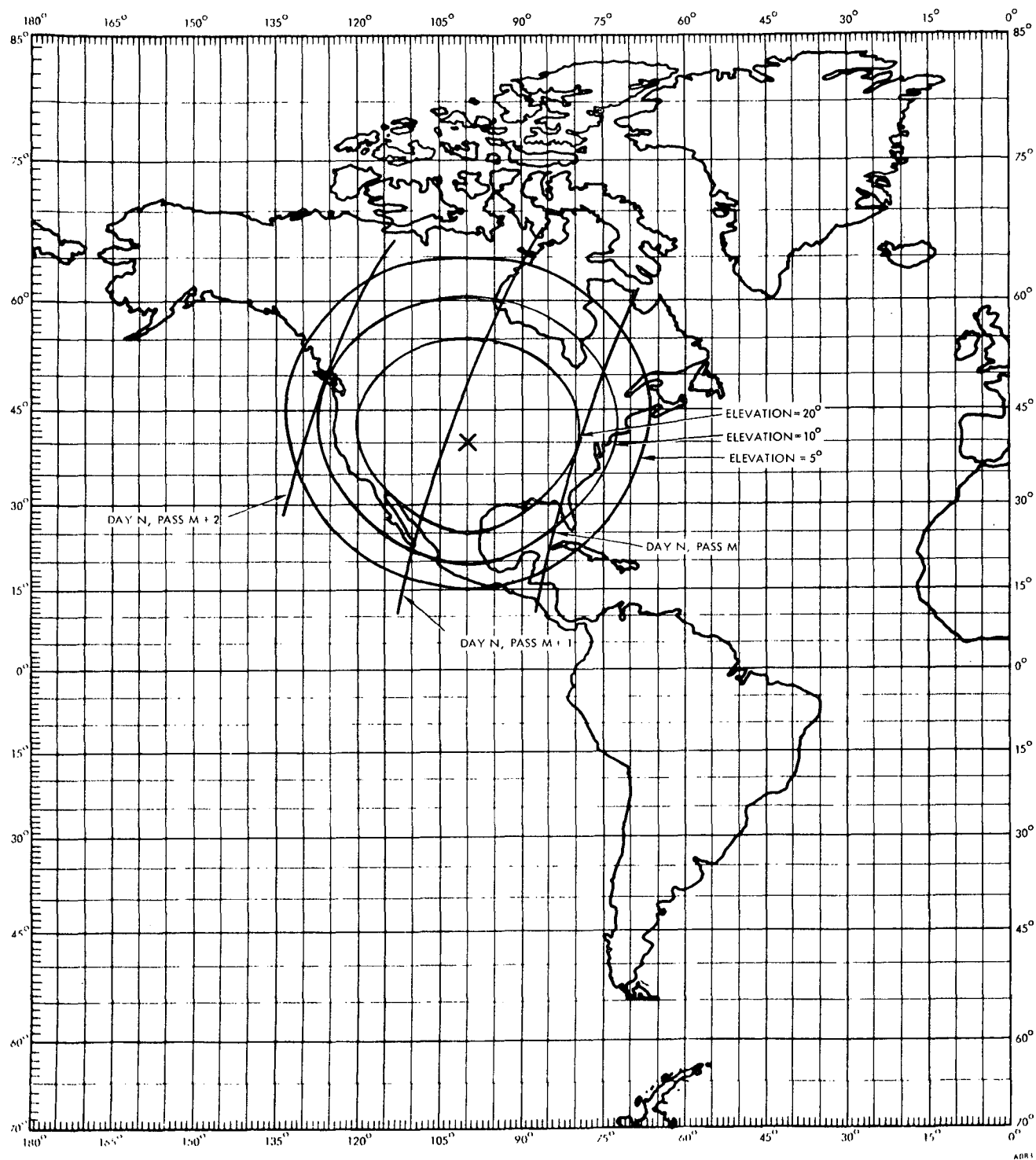


Figure 3.2.2. Satellite Coverage for Ground Station Elevation Angle Above 5°, 10°, and 20°

demonstrated by this figure is the relationship of consecutive satellite orbits. This shows that a Regional Collection Center could obtain information from as much as three consecutive orbits. A Local User Terminal most likely will not be interested in data from outside the 20° circle, and therefore will normally not be subjected to consecutive passes.

For a single pass the satellite will be in view of the ground station for about 10 minutes (not exact; see Figure 3, 1-11). At a data rate of 200 MBPS this would give a total quantity of 1.2×10^{11} bits. This same amount could be available some 90 minutes later on the succeeding revolution. This could be repeated a third time, but then there would be a "rest period" of approximately 9 hours.

Quantity Desired

This is probably the most subjective and uncertain aspect of the system at this time. Possible user situations can be hypothesized that would vary over a range of 100-to-1. In fact, it may well be that actual users will desire this variation. The answer will be provided as the ERTS program moves into its experimental phase and utility of the gathered data is evaluated.

3.2.3 Timeliness of Data

To project time requirements for users of earth resource data, one must consider the total potential system for these systems. It is almost certain that at least within the United States a central data processing facility will exist, with characteristics very similar to that with the present ERTS system. This means that user considerations can be broken into two categories. One of these categories is the group of users that want information concerning the area covered by this large central data processing facility. The only reason that this class of user would establish a local terminal for direct data reception would be to save the time involved in obtaining data from the large facility. This may include such users as: Agricultural, where a crop blight must be detected rapidly; Fishing Industry, where the desired information changes rapidly; Forestry, where the location and early detection of fires demands rapid access to the data; Localized pollution, such as the oil spills from off-shore drilling. Another category of users for local terminals will be those that are not located in the area serviced by this large facility. Typical of this group of users are foreign (underdeveloped) countries. It is expected that the main applications for these users will be agricultural, natural resources and mapping interests.

From the above discussion, it would seem desirable to have within the local terminal capability to output selected hard copy data within a short period of time after a particular pass. However, the bulk of the data could be processed over a period corresponding to the next desired pass of the satellite.

3.2.4 Resolution Requirements

The potential uses of Earth Resources type data depends to a large degree upon the resolution available and, hence, the degree of object detail that can be extracted from the images. To increase resolution, of course, requires increased data rate transmission and must be set at a reasonable value consistent with technical capability. The present resolution of ERTS-A and -B (approximately 200 feet) is suitable for many applications. However, many others require finer grain resolution. Thus, a compromise must be reached that provides most with the required resolution, but does not penalize many with excessive data rate.

The Woods Hole Summer Session [1], conducted by the National Academy of Science has done much to gather the opinions of users in many diverse areas. This data has been summarized by Norwood [2] and is stated in Table 3.2.4-1. Another article by Park [3] has catalogued many potential applications in the fields of agriculture and forestry. The resolution required for these is shown in Table 3.2.4-2 by number of applications requiring a given resolution.

Those users desiring less than 10 meter resolution would require so much data that transmission would be limited to a few bands (approximately two). This would eliminate the desirable spectral comparison features and would increase the cost unduely for the users requiring less resolution. Thus, it would seem that the system under consideration should have a resolution in the vicinity of 30 meters (70-100 feet).

Table 3.2.4-1. Example User Requirements (Platform in 150-500 n.m. Orbit)

	Wavelength (μ)	Resolution	Observation Interval
River and Delta Pollution	3.5-4.1	30M	2 a day
Agriculture and Forestry	0.5-12.0	60	2 weeks
Iceberg Tracking (Small and Drifting)	3.5-4.1	60	daily
Geological Survey	0.5-12.0	90	6 mos.
Thermal Mapping Near Shore	3.5-4.1	100	2-4 a day

Table 3.2.4-2. Categories of Uses in Forestry and Agriculture

Number of Applications	Required Resolution
4	50 meters
7	30 meters
3	20 meters
16	less than 10 meters

3.2.5 Number of Spectral Bands

The number and width of spectral bands may be one of the most difficult tasks in configuring an operational version of an Earth Resources spacecraft. It is certain that experience with ERTS-A and -B will contribute greatly to this problem, but there may never be absolute agreement among all prospective users. Some guidelines may be obtained from user experience with aircraft multispectral data that has been extrapolated to spacecraft platforms.

A survey conducted by Lorsch [4] in the varied agricultural applications of multispectral sensor data has shown that of twelve (12) categories of uses eight (8) could use spacecraft platforms. Of these eight, three wanted three band coverage and five wanted six bands. Thus, it would seem that a minimum of six bands should be included in the prospective system. From the previous data compiled by Norwood, it is seen that this information ranges from 0.5-12.0 microns.

3.3 Sensor Characteristics

The sensor characteristics, especially output data rate and format, have several major impacts on the overall system design. The data rate directly controls the transmission link parameters, and the format controls, to some extent, the recording, processing and display characteristics. Predicting the exact nature of future ERTS sensors is impossible since so many variations are possible. However, some reasonable estimate must be made to proceed with the system configuration. This section discusses briefly the present Return Beam Vidicon (RBV) and Multi-Spectral Scanner (MSS) planned for ERTS-A, and then extrapolates these parameters into possible configurations have total output data rates of 100 - 200 Mbps. The possible format of this data is also discussed.

3.3.1 ERTS-A Sensors

The following descriptions are largely paraphrased from "Design Study Specifications for the Earth Resources Technology Satellite: ERTS-A and -B," NASA/GSFC, Revision B, January 1970. In both sensors a swath width of 100 NM is used, with simultaneous images being scanned in several spectral regions. Although the resolutions are similar (within 2:1) the output data format is very different. Hence, the sensors are discussed separately below.

3.3.1.1 Return Beam Vidicon

The RBV which will be used on ERTS-A is a three camera system which simultaneously exposes the same 100 NM by 100 NM scene to all three cameras and then sequentially reads out the cameras, one complete frame at a time. The basic frame repetition rate is 25 seconds which corresponds to a ground trace movement of 90 NM, hence, allowing a 10% overlap in adjacent frames along track. The major parameters of the RBV are given in Table 3.3.1.1-1. The data readout format characteristics are shown in Figure 3.3.1.1-1.

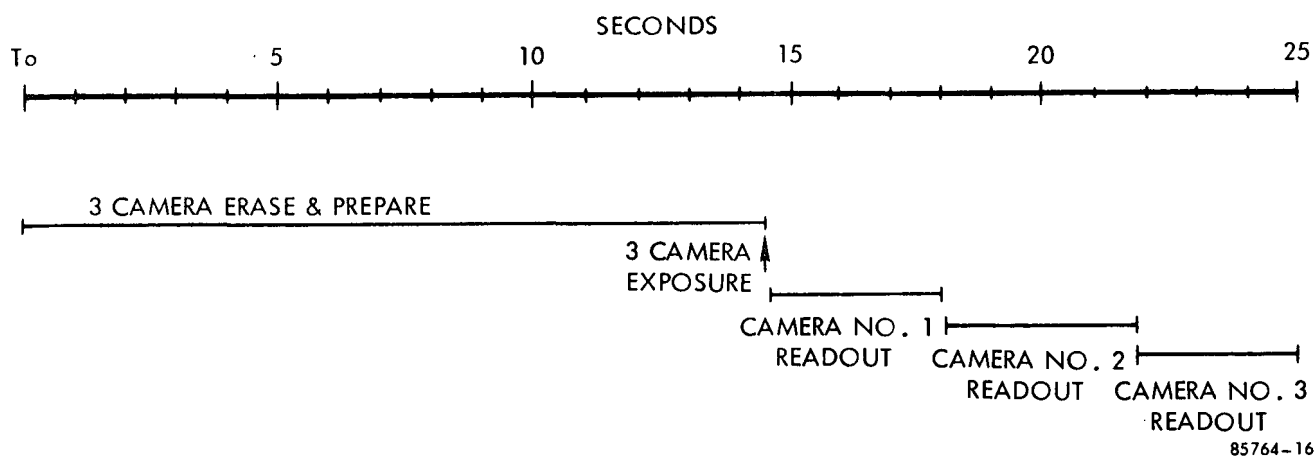


Figure 3.3.1.1-1. ERTS-A RBV Timing Diagram

Table 3.3.1.1-1. RBV Characteristics for ERTS-A

	Camera 1	Camera 2	Camera 3
<ul style="list-style-type: none">● Resolution (at max. scene high-light contrast)● Edge Resolution (% of center)● Signal-to-noise ratio (@ 10 TVL)● Dynamic Range● Grey Scale (2 transmission steps)● Shading (max. vert. & horizontal)● Residual Image (max.)● Horizontal Scan rate (lines/sec)● Number of Scan Lines● Readout time (seconds)● Video bandwidth (MHz)● Time between picture sets (sec)● Exposure time (milliseconds)● Image Distortion (max.)● Deflection skew (max.)● Size & centering shift (max.)● Spectral bandwidth (nanometers)	4500 TVL* 80 33 dB 50:1 10 15% 3% 1250 4200 3.5 3.5 25 8, 12 or 16 1% ±0.50% ±2% 475-575	4500 TVL 80 33 dB 50:1 10 15% 3% 1250 4200 3.5 3.5 25 8, 12 or 16 1% ±0.50% ±2% 580-680	3400 TVL 80 25 dB 50:1 10 15% 3% 1250 4200 3.5 3.5 25 8, 12 or 16 1% ±0.50% ±2% 690-830

*TVL - Television Lines

Some further useful parameters can be quickly calculated from the above tabulated data.

$$\text{Ground Cell Size} = \frac{(100 \text{ NM}) (6080 \text{ ft/NM})}{4200 \text{ Scan Lines}} = 145 \text{ ft/line}$$

$$\begin{aligned} \text{Equivalent Digital Data Rate} &= \frac{(4200 \text{ samples/line})^2 (4 \text{ bit quantization})}{3.5 \text{ seconds}} \\ &= 20 \text{ Mbps} \end{aligned}$$

The four bit quantization is used as a reasonable value consistent with the characteristics of these cameras.

3.3.1.2 Multi-Spectral Scanner

The MSS is an object plane scanner which will provide radiometric measurements and imagery of the ground scene in the following spectral bands:

1. 0.5 to 0.6 microns
2. 0.6 to 0.7 microns
3. 0.7 to 0.8 microns
4. 0.8 to 1.1 microns
5. 10.5 to 12.6 microns (ERTS-B only)

The cross track scanning is provided by a high duty cycle (65%) rocking mirror (15.2Hz) over $\pm 5.8^\circ$. The image has an instantaneous field of view of 230 ft. by 230 ft. The image is relayed with fiber optic bundles, which also determine the aperture, to PMT detectors for Bands 1, 2, and 3; Si PD for Band 4; and intrinsic IR detectors for Band 5. Six detectors scan the scene (in each band) (except for Band 5 which will have 2) simultaneously. This reduces the required mirror scan rate for complete coverage of the 100 by 100 n.mi. scene. This operation is illustrated in Figure 3.3.1.2-1 for the ERTS-A MSS.

From the major MSS parameter values some further parameters can be calculated.

$$\text{Ground Cell Size} = \frac{21,300 \text{ ft/sec ground vel.}}{(6 \text{ lines/scan})(15.2 \text{ scans/sec})} = 234 \text{ ft/line}$$

$$\text{Active scanning time (for 6 lines)} = \frac{(.65 \text{ duty cycle})}{(15.2 \text{ scan/sec})} = 42.7 \text{ Msec}$$

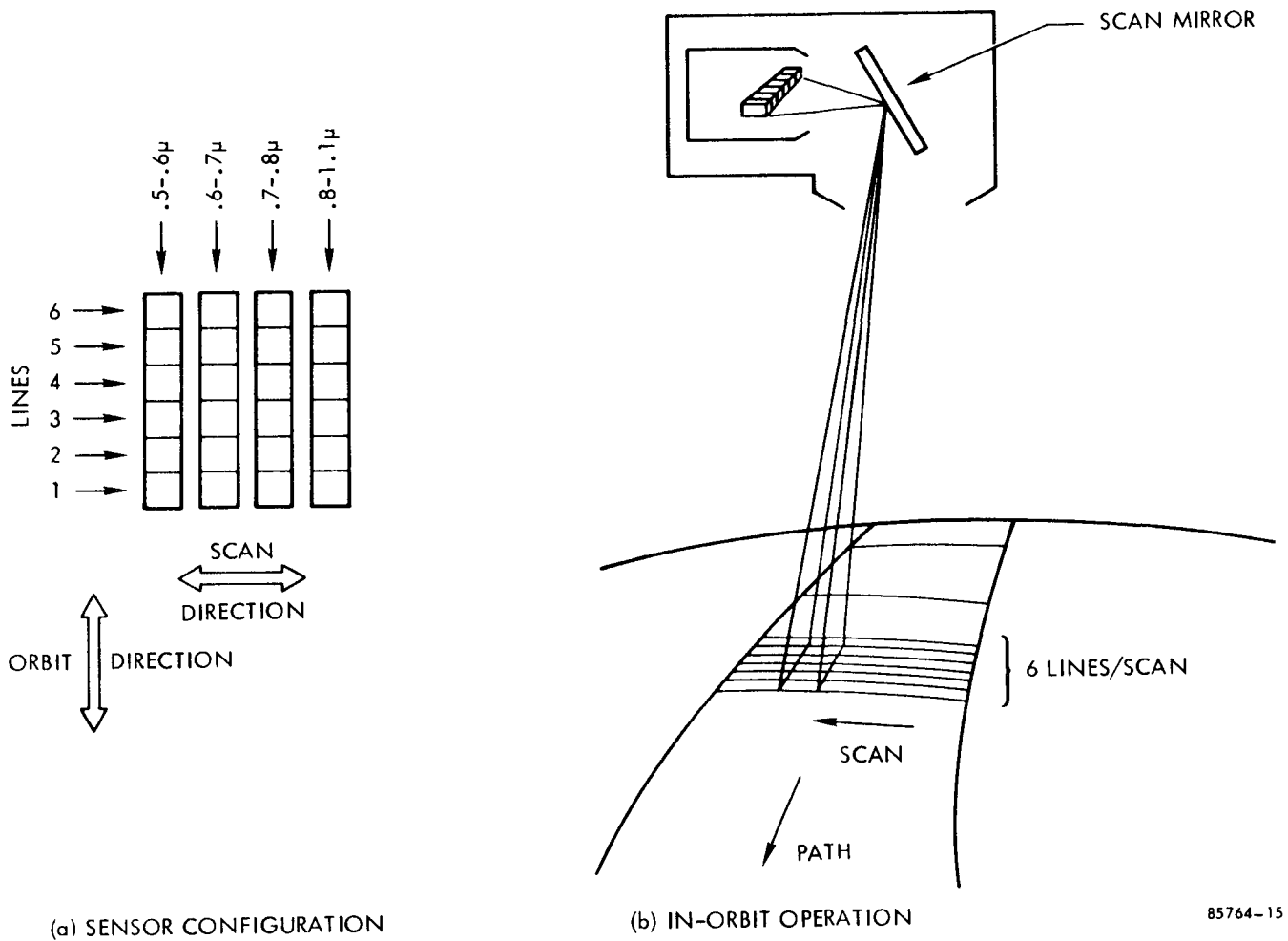


Figure 3.3.1.2-1. ERTS-A MSS Operation

Hence, equivalent scan time per line = 7.1×10^{-3} sec.

$$\text{Digital data rate} = \left(\frac{608,000 \text{ ft.}}{234 \text{ ft/cell}} \right) \left(\frac{1}{7.1 \times 10^{-3} \text{ sec}} \right) (6 \text{ bit quantization}) = 2.2 \text{ Mbps}$$

3.3.2 Possible 100-200 Mb/s Sensor Characteristics

To get from the present sensors to one having the output data rates under consideration one must change one or more of the following parameters.

- ground resolution
- number of gray shades (quantitization levels)
- number of spectral bands

Based upon the user considerations discussed previously, it is apparent that higher resolution is desired for several applications. Increasing the resolution of the RBV cameras will require a major expenditure and does not seem very promising. This is illustrated in a presentation by Mr. George Barna of RCA where he discussed improving on the present 90 line-pairs/mm of the RBV: [5]

"Preliminary investigations have been conducted toward improving the resolution of the vidicon to 120 line pairs/mm. There is some encouragement that such a goal can be realized, but considerable experimental work remains to be done."

The lower duty cycle of the RBV also requires a higher transmitted data rate than that for the MSS to achieve the same ground resolution unless on-board buffering is utilized. For these reasons, a potential future sensor will be hypothesized in terms of the MSS.

One desirable characteristic to have in a future MSS is a number of parallel sensors per spectral band equal to 12. With this number of parallel data channels, a user with lower resolution requirements could easily half, third, or quarter the resolution by averaging cell intensity of adjacent samples and tracks. This could be done in real time as the data is received, and thus save the additional cost of higher speed recorders and processors. It could also be accomplished by an on-board processor to service the Mode II requirement. Since the present MSS uses 6 parallel scanners per spectral band it should not be unreasonable to expect 12 in the future.

As discussed in an earlier section, some users desire a resolution of approximately 70 feet. For the satellite ground trace velocity of 21,300 ft/sec. this requires a scan rate of

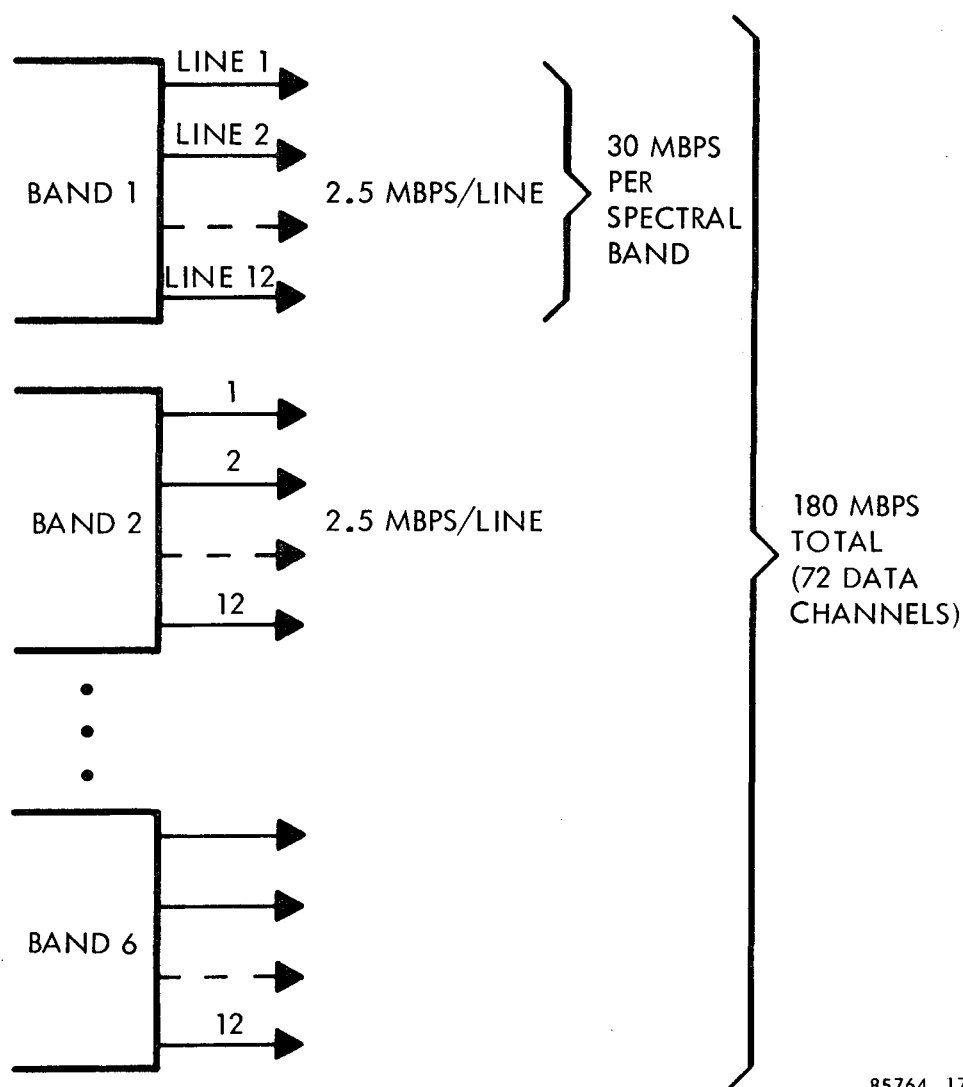
$$\frac{(21,300 \text{ ft/sec})}{(12) (70 \text{ ft})} = 25.4 \text{ scans/second}$$

which seems reasonable in terms of the present MSS scan rate.

For swath width of 100 N.M., a duty cycle of 0.65, and 6-bit quantization the data rate per line per spectral band can be calculated as

$$(6 \text{ bits}) \left(\frac{608,000 \text{ ft.}}{70 \text{ ft/cell}} \right) \left(\frac{25.4 \text{ scans/sec}}{.65} \right) = 2.05 \text{ Mbps}$$

Since twelve parallel lines per spectral band are scanned simultaneously, the data rate per spectral band will be 24.4 Mbps. When all synchronization and formatting bits are considered, the total data rate per spectral band would be approximately 30 Mbps. It seems reasonable to expect at least six spectral bands, which yields a total data rate of 180 Mbps. This value is near the upper limit specified and therefore verifies the need for considering high data rate systems. The data format resulting from such a sensor configuration is illustrated in Figure 3.3.2-1.



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Figure 3.3.2-1. Output Format of Baseline MSS

3.3.3 Data Collection System (DCS) Characteristics

The ERTS system will have a DCS which provides capability for relaying data from remote ground emplaced sensors to the earth stations which are mutually visible by the satellite. Reference [6] describes the telecommunication system for ERTS A and B including a summary of the DCS. Salient features of the system are discussed below. Radiation was selected to provide the design and development for the original systems including the platform, spacecraft receiver, and earth receiving site equipment (RSE) and therefore is well aware of the system performance to be expected.

The DCS was designed to receive data from up to 1000 platforms every 12 hours with 95% probability of successful reception. To conserve power, the remote platforms are designed to transmit short bursts of information (approximately 100 bits) every 90 or 180 seconds. The randomness of the clocks between platforms assure that bursts from all platforms will be distributed during the satellite passtime. The information rate within each burst is 2.5 kb/s.

Each burst of data contains synchronization and platform identification bits in addition to the data. The information rate is passed through a rate 1/2 convolutional encoder to produce a symbol rate of 5 kb/s. This data frequency modulates a 400 MHz carrier with a deviation of approximately 3.5 KHz. The spacecraft receiver down-converts the 400 MHz signal to a center frequency of 1.024 MHz which becomes a subcarrier modulating the S-Band downlink. Doppler shifts plus frequency tolerances lead to a requirement for 100 KHz bandwidth at the ultimate RSE demodulator.

The RSE consists of a six-channel demodulator, a bit synchronizer, a maximum likelihood convolutional decoder, and a data formatter. The 1.024 MHz subcarrier is input to the RSE where a burst of data is demodulated by the appropriate channel and fed to the bit synchronizer. If bit synchronization is achieved valid data is assumed, and vice versa.

Tests at Radiation have shown that the required performance of 10^{-3} message error probability (10^{-5} bit error probability) is achieved with a signal to noise ratio of 0 dB at the RSE measured in the 100 KHz bandwidth. This figure is better than original expectations and will be used for analysis purposes in this study.

It is expected that any operational earth observation system will have a requirement for a DCS type capability. While a comprehensive treatment of this subject is beyond the scope of this study effort, it is shown that such a capability can be incorporated into the system configuration presented in this report. The basic constraint in this result is that the platform and RSE required are those which presently exist. This may not be the most effective approach, especially with

respect to the RSE, and further study should investigate placing varying degrees of additional capability in the spacecraft.

3.4 Frequency Selection Considerations

The purpose of this section of the report is to discuss the frequency dependent parameters of the envisioned system and to provide some insight into a rationale for selection of operating frequencies. Major emphasis is placed upon performance factors, for example, atmospheric absorption as a function of frequency, in this discussion. Frequency allocation and component availability are other factors which must be considered.

References [7-18] are provided for background information.

3.4.1 Summary of Frequency Selection Criteria

The primary considerations in establishing operating frequencies for the earth observation system described herein will be:

- Required bandwidth
- Performance/Reliability Considerations
- Hardware Constraints

Perhaps the most important of these is bandwidth which must be overlaid and compared to the existing allocations. The Mode I system operation will require a minimum of 200 MHz RF bandwidth to support the 100-200 Mb/s data rate. It appears that, when allocations are also considered, X-Band or higher will be necessary.

The Mode II system requires less bandwidth due to a lower data rate. Still, as much as 5 MHz may be necessary. While operation at VHF/UHF is potentially desirable for this application, spectral crowding makes the possibility of such an occurrence uncertain. It should be possible to obtain the required 5 MHz (this may become 10 MHz or so in the event of a digital Mode II system) bandwidth in the 1 - 3 GHz range. Thus, one system approach is labeled the S-Band System.

The performance/reliability considerations will be used to evaluate the effect of all noise sources, RFI, and losses. Since losses other than path losses and noise effects do not vary by an extreme amount, with the exception of rainfall effects, over the 1-10 GHz band, RFI considerations move to a dominant position in this category. Because of advantages detailed in Paragraph 3.4.3, usage, both

commercial and governmental, of the 1-10 GHz band is increasing making RFI a crucial issue. These performance aspects must be balanced and weighted against available hardware in order to maximize reliability and to avoid recommendations which would entail unnecessary hardware complexity and/or development.

A trade-off quickly becomes apparent between operating at higher frequencies (> 10 GHz) to avoid RFI and the resultant degraded performance due to atmospheric and related phenomena. While it is feasible to operate at carrier frequencies around 15-20 GHz and meet the performance requirements imposed by the present application, to do so is increasingly expensive as frequency increases. Either performance must be sacrificed or cost penalties incurred (or both).

A related factor which also influences the choice of frequencies is equipment availability. For example, development is required for any system operating at 20 GHz. This is another factor favoring lower frequencies.

The conflicting aspects of performance and hardware availability on the one hand and allocations on the other will be made more apparent in the remainder of this section.

3.4.2 Allocation Considerations

Since the eventual communication network will operate in part outside the boundaries of the United States, the frequency assignment problem must be considered on an international basis. For this international scope, it is a matter of U.S. Government policy to seek international agreement. Any negotiations are performed through the State Department office of Transport and Communications with the principal international agency involved being the International Telecommunications Union (ITU), Geneva, Switzerland. This union publishes regulations from time to time as the state-of-the-art in radio communication demands. Once adopted, these regulations have the force of a treaty and, therefore, provided the guidelines for the frequency selection aspects of this study effort.

Specifically, Study Group IV of the International Radio Consultative Committee (CCIR), a branch of the ITU, is charged with studying matters of significance to space communications. As a result of recommendations of Study Group IV and the CCIR, frequency assignments abstracted in Table 3.4.2 have been made for space use. The range of frequencies enumerated in this table is restricted to our primary band of interest, 1-20 GHz.

Table 3.4.2. Frequency Allocations for Space

Frequency MHz	Service	Category	Region
1400-1427	Radio astronomy	P	1, 3
1427-1429	Space (telecommand)	P, S	
1525-1535	Space (telemetry)	P, S P	1, 3
1535-1540	Space (telemetry)	P	
1540-1660	Aeronautical radio-navigation	P	
1660-1664.4	Meteorological satellites	P, S	
1664.4-1668.4	Meteorological satellites	P, S	
1664.4-1668.4	Radio astronomy	S	
1668.4-1670	Meteorological satellites	P, S	
1690-1700	Meteorological satellites	P, S	
1700-1710	Space research	P P, S	1, 3
2110-2120	Space research (deep-space telecommand)	FN	
2290-2300	Space research (telemetry and tracking in deep space)	P	2
2690-2700	Radio astronomy	P	
3165-3195	Radio astronomy	FN	
3400-4200	Communications satellite (satellite to earth) includes associated telemetry and tracking	P, S	

Table 3.4.2. Frequency Allocations for Space (Continued)

Frequency MHz	Service	Category	Region
4200-4400	Aeronautical navigation	P	
4400-4700	Communications satellite (earth to satellite) and associated tele-command	P, S	
4800-4810	Radio astronomy	FN	
4990-5000	Radio astronomy	P, S P	1, 3 2
5000-5225	Space research	S	
5670-5725	Space research (deep space)	S	
5725-5850	Communications satellite (earth to satellite) and telecommand	P, S	1
5800-5815	Radio astronomy	FN	
5850-5925	Communications satellite (earth to satellite) and telecommand	P, S	1, 3
5925-6325	Communications satellite (earth to satellite) and telecommand	P, S	
7120-7130	Space (telecommand)	FN	
7200-7250	Meteorological satellite (including tracking and telemetry)	FN	
7250-7300	Communications satellite (satellite to earth)	P, S	
7300-7750	Meteorological satellite (including tracking and telemetry)	P, S	

Table 3.4.2. Frequency Allocations For Space (Continued)

Frequency MHz	Service	Category	Region
7300-7750	Communications satellite (satellite to earth)		
7250-7750	Passive communications satellite systems	FN	
7900-7975	Communications satellite (earth to satellite) and telecommand	P, S	
7975-8025	Communications satellite (earth to satellite) and telecommand	P	
8025-8400	Communications satellite (earth to satellite) and telecommand	P, S	
8400-8500	Space research	P P, S	1, 3
8680-8700	Radio astronomy	FN	
9975-10025	Meteorological satellite (weather radar)	FN	
10.68-10.7	Radio Astronomy	P	
14.3-14.4	Radio-Navigation Satellite	P	
15.25-15.35	Space Research		
15.35-15.4	Radio Astronomy	P	
15.4-15.7	Aeronautical Radio Navigation	P	
19.3-19.4	Radio Astronomy	P	

The regions referenced in Table 3.4.2 are three in number and are precisely defined by the ITU. Generally speaking, Region 1 embraces Europe and Africa; Region 2, North and South America and Hawaii; and Region 3 Australia-Asia. As the table indicates, the regulations occasionally permit different usage in different regions. Also different usage is permitted on a national basis or in areas less than regional in extent in some cases. Absence of a regional designation in the table indicates that the assignment indicated is applicable on a worldwide basis.

The categories noted in Table 3.4.2 are P for primary service, S for secondary service, and P, S for primary services which are shared with other services; for example, various ground based services. The FN notation implies a footnote to the ITU Frequency Allocation Table which stipulates modifications governing the allocation. For brevity, these footnotes are not included in this discussion. The significance of these allocations and service designations is that the use of the services indicated must be protected from interference by any other users. In all cases the primary user has priority over the secondary user.

Current heavy usage of the allocated frequency bands by U.S. agencies includes heavy S-Band operation by both NASA and SCF for command and telemetry, commercial utilization of frequencies generally in the 4 to 6 GHz range, and the DOD systems operating primarily in the X-Band range around 7 to 8 GHz. It is felt that the commercial and military bands must be avoided.

Recent indications are that considerable variation in the allocations available, especially above 10 GHz, will soon be adopted by the ITU. Generally such variation increases the space service in the 10-15 GHz band*, increases the bandwidth available at 8.4 GHz and allocates the 21.2-22 GHz band to operational earth resource observation systems. As a consequence, the results of these anticipated actions have been considered in this study effort. Specifically, as originally planned, a frequency of 15.25 GHz is utilized for baseline computations and analysis of the Mode I system. However, the effect of operation at both 8.4 and 21.2 GHz is considered. As expected, cost and performance aspects would indicate selection of the lowest available frequency of operation.

3.4.3 Performance Factors

Many considerations are involved in selection of an operating frequency, but a major factor is the impact on performance of the communication link. In general, the link design must ensure satisfactory probability of adequate signal strength

* However, operation here is being considered by a multitude of systems.

at the receiver so that when receiver noise and external noise are added, the signal-to-noise ratio at the receiver output permits the required data accuracy. Since practically all the significant factors which influence the link performance are frequency dependent, the nature of the relationship between frequency and these parameters must be clearly understood and evaluated in the link design. The performance aspects must be balanced against such things as RFI, allocations, and hardware limitations to determine an optimum solution. When these performance considerations are then combined with the other constraints, which proper weighting for each factor, the best operating frequency can be selected.

To discuss link performance, consider the product of transmitted data quality and quantity as a figure of merit F . The one-way transmission equation can then be written in terms of this product as:

$$F = (S/N)B = \frac{G_T G_R P_T \lambda^2}{(4\pi)^2 R^2 L kT}$$

In this equation the signal-to-noise ratio represents signal quality and the bandwidth, B , represents quantity. This result then provides a basis for evaluating system performance as a function of frequency, the frequency dependent parameters being the antenna gains, the free space path loss $\lambda^2/(4\pi R)^2$, the losses L , and the receiving system noise temperature T . Additionally, the transmitted power is frequency dependent due to hardware constraints, which are discussed in Section 5.0.

3.4.3.1 Losses

Many frequency dependent losses which are not explicitly included in the above equation must, nevertheless, be included in the communication link evaluation. Major emphasis should be placed on such factors as atmospheric absorption, rain attenuation, and antenna pointing and tracking losses with secondary consideration for transmission line losses, polarization losses and other incidental losses which are frequency dependent to a lesser degree.

The free space path loss can be expressed in a more convenient form (in dB) as:

$$L = +36.58 + 20 \log_{10} f + 20 \log_{10} R$$

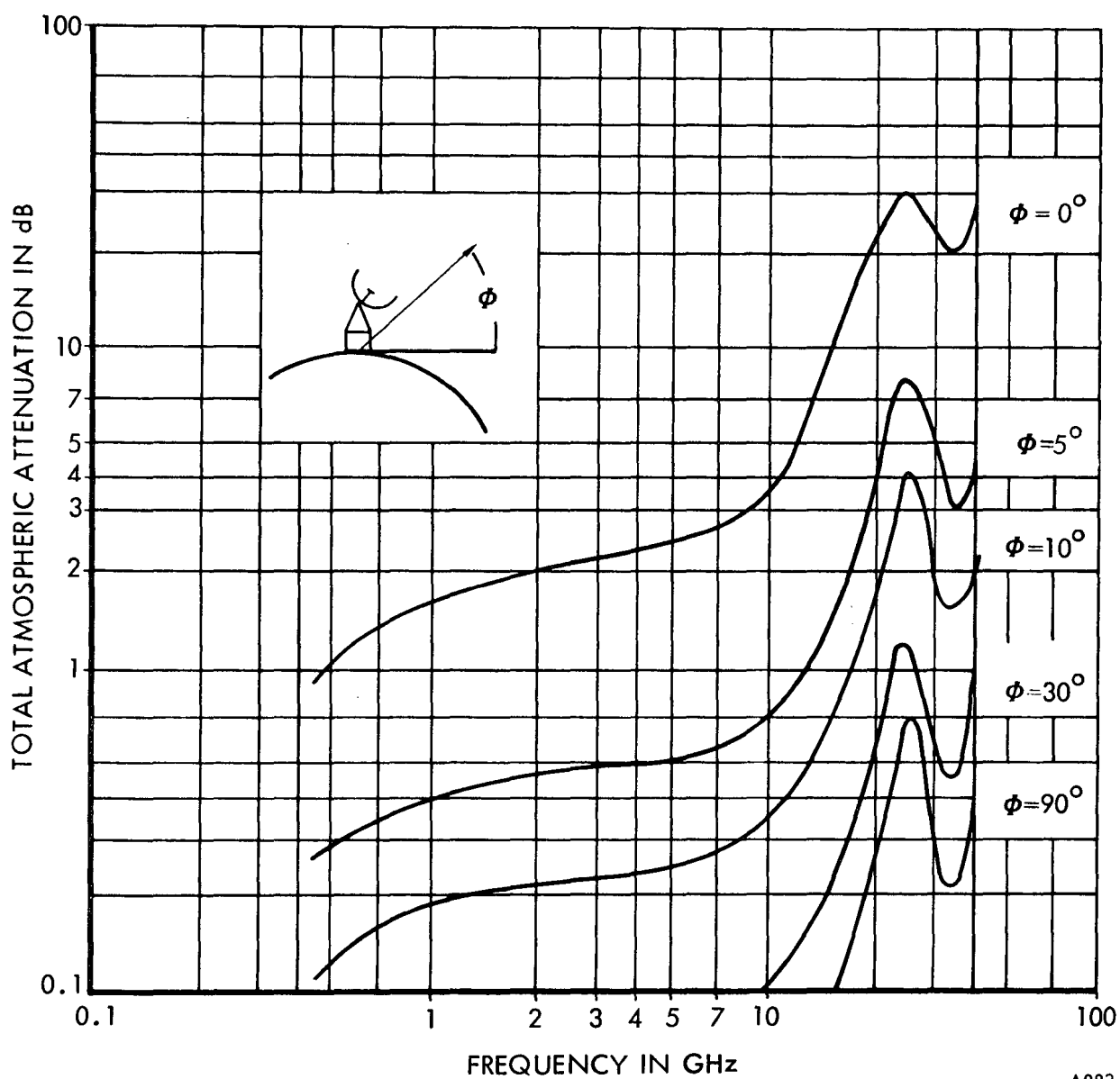
where f is expressed in megahertz and the range R in statute miles. If only the frequency dependence is considered (R is held constant), the path loss in dB is seen to increase logarithmically with frequency. That is, an increase in frequency from X-Band (8 GHz) to Ku-Band (16 GHz) would produce an attendant increase in path loss of 6 dB. However, this increased path loss can be more than offset by the corresponding increase in antenna gains if constant apertures are maintained. For the situation in which one constant gain and one constant aperture antenna are utilized, path loss variations with frequency are exactly negated in the overall link budget. Since an increased frequency generally allows greater information bandwidth, the higher frequencies are advantageous for the Mode I system.

Unfortunately, a decision to increase frequency and thus hopefully achieve increased performance capability is not so straightforward as might be indicated at this point. The primary elements which complicate the issue, insofar as losses are concerned, are atmospheric absorption and rain (or moisture) attenuation, both of which are increasingly important considerations for frequencies above 10 GHz. As a general rule attenuation increases proportionally with frequency, thus, imposing rather severe penalties on links designed for 15 GHz or above.

The effect of atmospheric attenuation as a function of frequency is illustrated in Figure 3.4.3.1-1. In this figure the antenna elevation angle, and thus range through the atmosphere, is a parameter. The attenuation for elevation angles above 10° and frequencies below 10 GHz is small. Therefore, atmospheric attenuation is not a major factor for the local user terminals. At 15.25 GHz and 5° elevation, the baseline conditions for the Regional Collection Center, an attenuation of 1.4 dB is encountered and is a significant factor in the link budget.

Figure 3.4.3.1-1 vividly illustrates one of the disadvantages of operation in the 21.2 - 22 GHz band; namely, the proximity to the absorption peak due to H_2O . The attenuation at this frequency is on the order of 6.5 dB for a 5° elevation angle. This is a very significant loss and might constrain operation to a 10° minimum elevation angle where the loss is reduced to approximately 3 dB. Also illustrated is one of the advantages of a reduced carrier frequency to 8.5 GHz where the atmospheric attenuation is .6 dB or less.

A more significant factor, at least for X-Band frequencies and above and during periods of precipitation, is attenuation due to rainfall and related effects. Many references exist which present both experimental and theoretical



A082

Figure 3.4.3.1-1. Total One-Way Atmospheric Attenuation Due to Oxygen and Water Vapor as a Function of Frequency with Elevation Angle as a Parameter

models for propagation through the atmosphere, clouds, rain, etc. at radio frequencies. It is generally agreed that attenuation due to these effects can be severe and seriously degrade link performance, especially at frequencies above 10 GHz. However, there is a wide variance in expected attenuation values. Obviously this is due in part to the many variables which exhibit some degree of effect on the attenuation. Examples are rainfall rate, cloud density, cloud height, etc. Certainly wide variation is expected in local conditions.

Nevertheless, it is desirable in configuring a link to be able to predict with some degree of confidence the expected attenuation due to these statistical variables. The results discussed here lend such confidence to one model which may be used for such calculations.

Recent empirical data has been obtained from ATS-V experiments which has provided valuable insight into attenuation expected in satellite-to-ground links due to rainfall [14]. The measured data at the Rosman, N.C. site was obtained for a carrier frequency of 15.3 GHz and a ground elevation angle of approximately 42° . The data has been found to exhibit reasonable correlation with a model recommended by the CCIR (Consultative Committee for International Radio) and described by Benoit [16]. This correlation is illustrated by the data compiled in Table 3.4.3.1-1. The figures indicated for ATS-V measurements represent some smoothing applied to the attenuation, and best results are achieved by considering space averaged rainfall rates. The good agreement exhibited lends confidence to utilization of the CCIR model at other frequencies and elevation angles.

Table 3.4.3.1-1. Rainfall Attenuation Data

Rainfall Rate (mm/HR)	Benoit Prediction (dB Attenuation)	ATS-V Data (dB Attenuation)
6	2	1.8
12	5	5.0
20	8	8.5
40	18	16.0

Figure 3.4.3.1-2 gives the attenuation constant (dB/km) recommended by the CCIR as a function of frequency and precipitation rate in mm/hr. The remaining factor is then the ceiling altitude for which the CCIR utilizes 3 km. This results

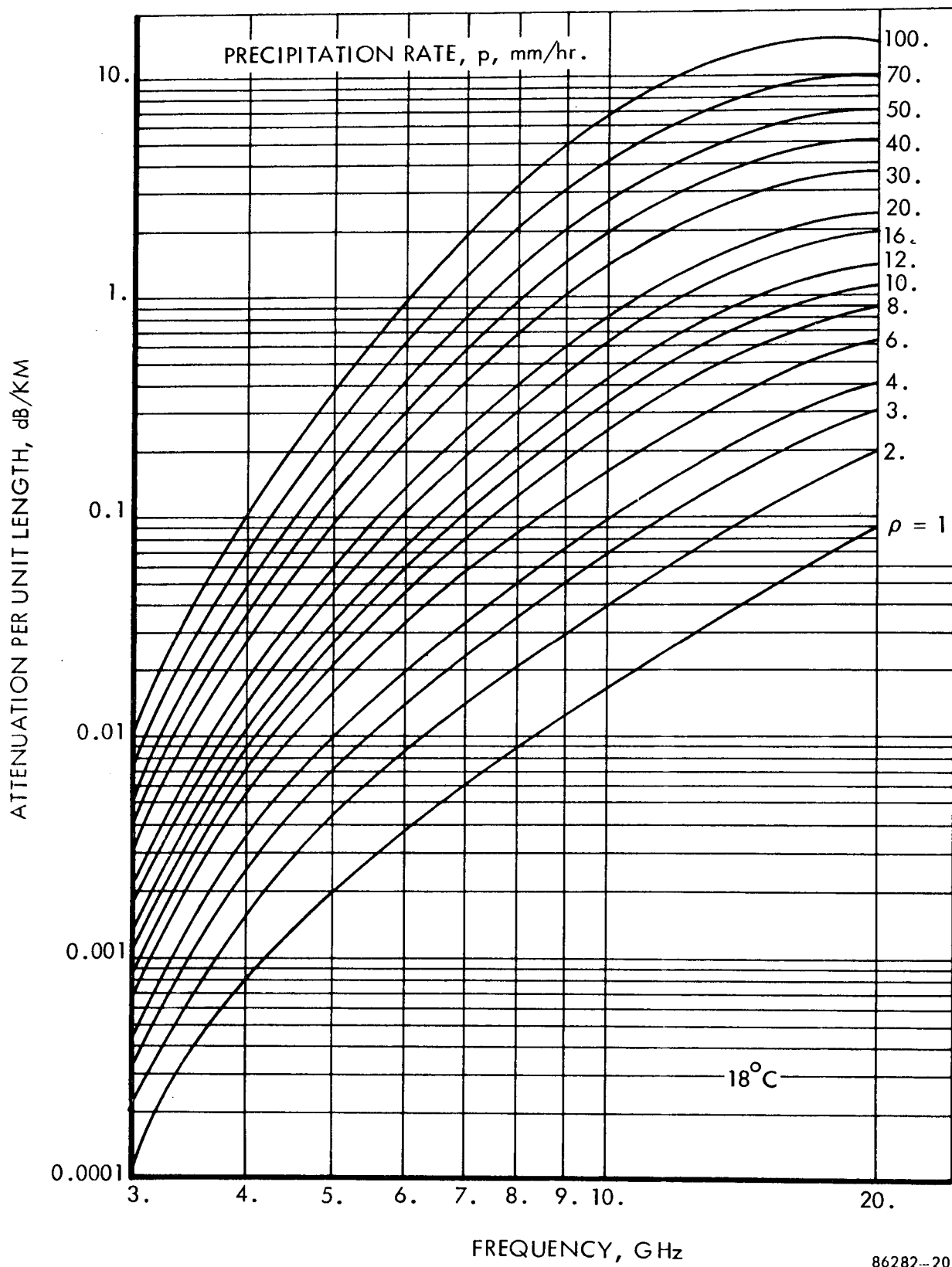


Figure 3.4.3.1-2. Attenuation (dB/Km) due to Rain

in a slant range of 34 km at 5° elevation and 18.5 km at 10° elevation. The resultant attenuation predicted for a precipitation rate of 4 mm/hr at the 5° elevation angle is 2, 9.2, and 15.3 dB for frequencies of 8.5, 15.25, and 21.2 GHz respectively. As illustrated below 4 mm/hr represents a reasonable design value for the present application.

Using the above rationale, the one-way attenuation for a frequency of 15 GHz is shown in Figure 3.4.3.1-3 as a function of rainfall rate and elevation angle.

Given that attenuation as a function of rainfall rate has been established, the rainfall rate for which the system is to be designed must be selected. This is best done by examining rainfall statistics for the expected area of operation. Typical of the type of data required is that shown in Figure 3.4.3.1-4. For such locations as Washington, D.C. and Honolulu moderate rains in excess of 4 mm/hour occur less than 60 hours of the year on the average which translates to less than one percent of the year.

At the Rosman, N.C. site data gathered over 1050 hours typically shows attenuations of 1 to 3 dB in light rains or dense fog; 3 to 7 dB in continuous rains (5 to 50 mm/hr), and a number of fades exceeding 12 dB in heavy thunderstorms. This data is summarized in Table 3.4.3.1-2 for the Rosman Site and is extrapolated to various antenna elevation angles in Figure 3.4.3.1-5. Based upon this extrapolated data, a link at 15 GHz designed for the 9.2 dB margin indicated for 4 mm/hr rainfall rates would suffer slightly less than 3% outage or degradation due to precipitation. This is a reasonable comparison to the 1% indicated for Washington, D.C. because Rosman has a greater annual rainfall. Thus, the 4 mm/hr appears to be a reasonable design goal for a system which can tolerate outages of 1 - 3%. For higher carrier frequencies an obvious tradeoff develops because of the increased margin necessary for equivalent operation.

Table 3.4.3.1-2. One Year Cumulative Attenuation at Rosman, N.C. Station (10/1/69 - 10/1/70) at 15.3 GHz

Attenuation Level	Percent of Time Attenuation Exceeded
3	1.0
6	0.38
9	0.21
12	0.078
15	0.045

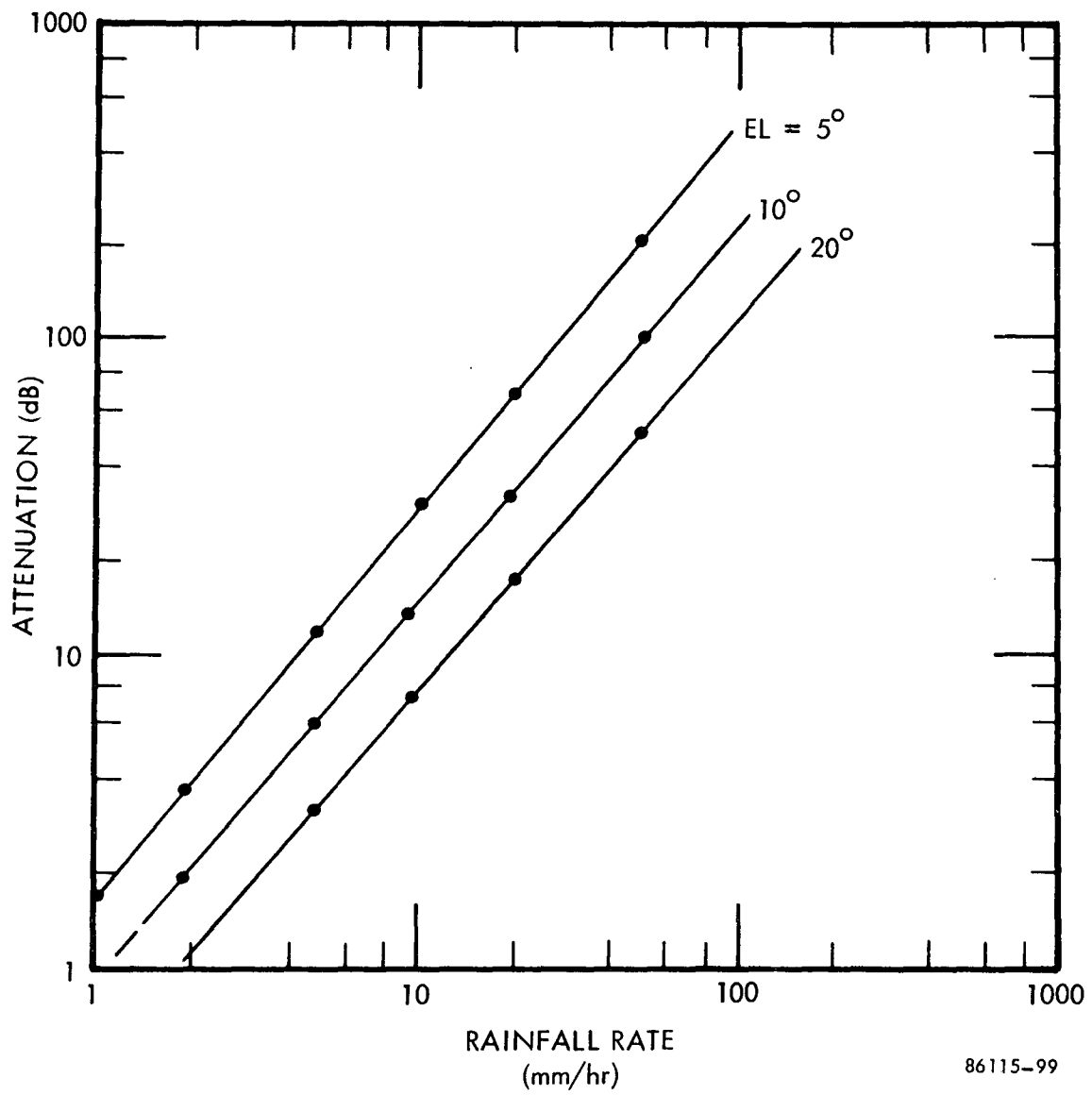


Figure 3.4.3.1-3. Rainfall Attenuation at 15 GHz
(Model from CCIR)

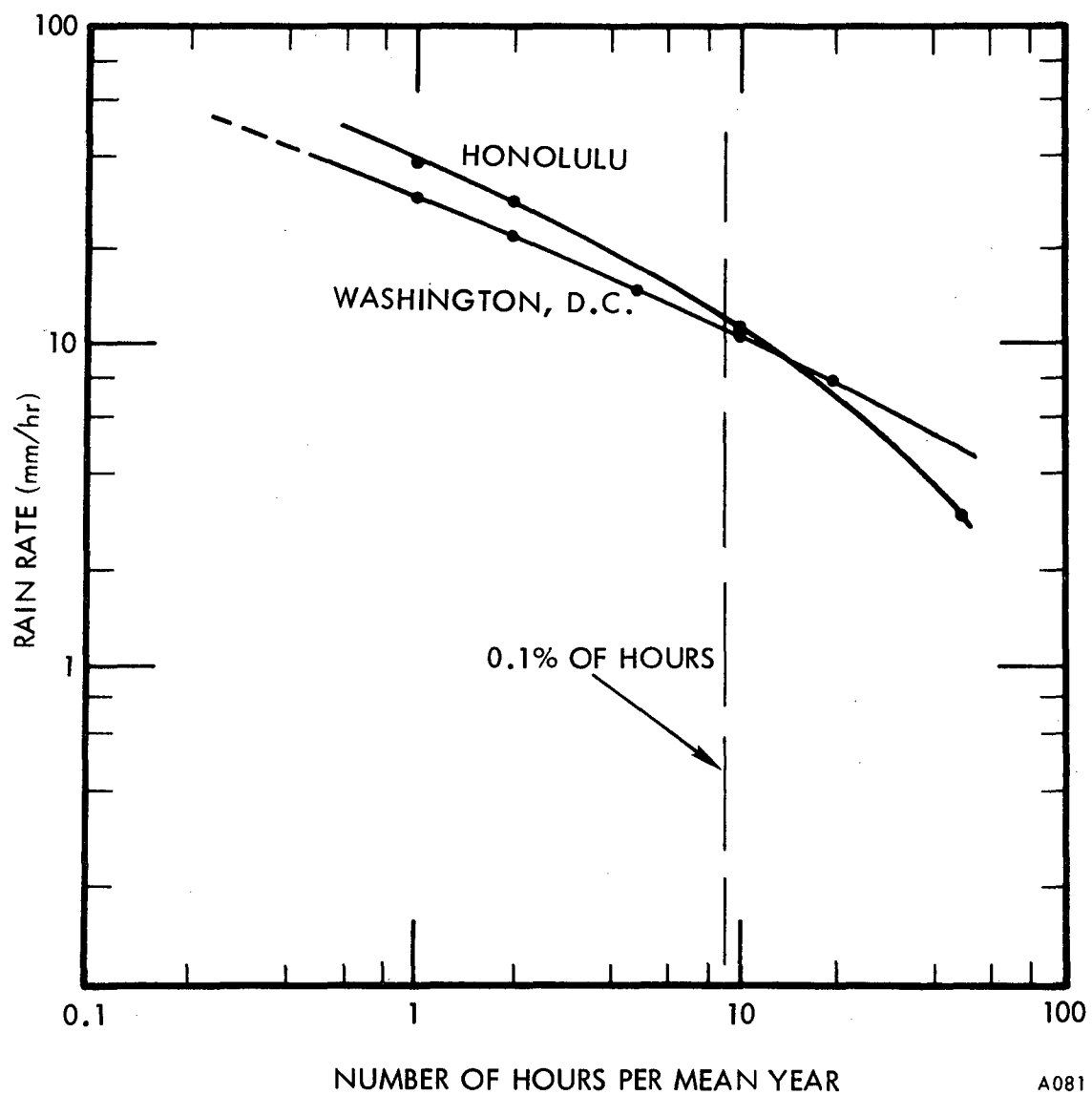


Figure 3.4.3.1-4. Distribution of Precipitation Rates at Washington, D. C. and Honolulu

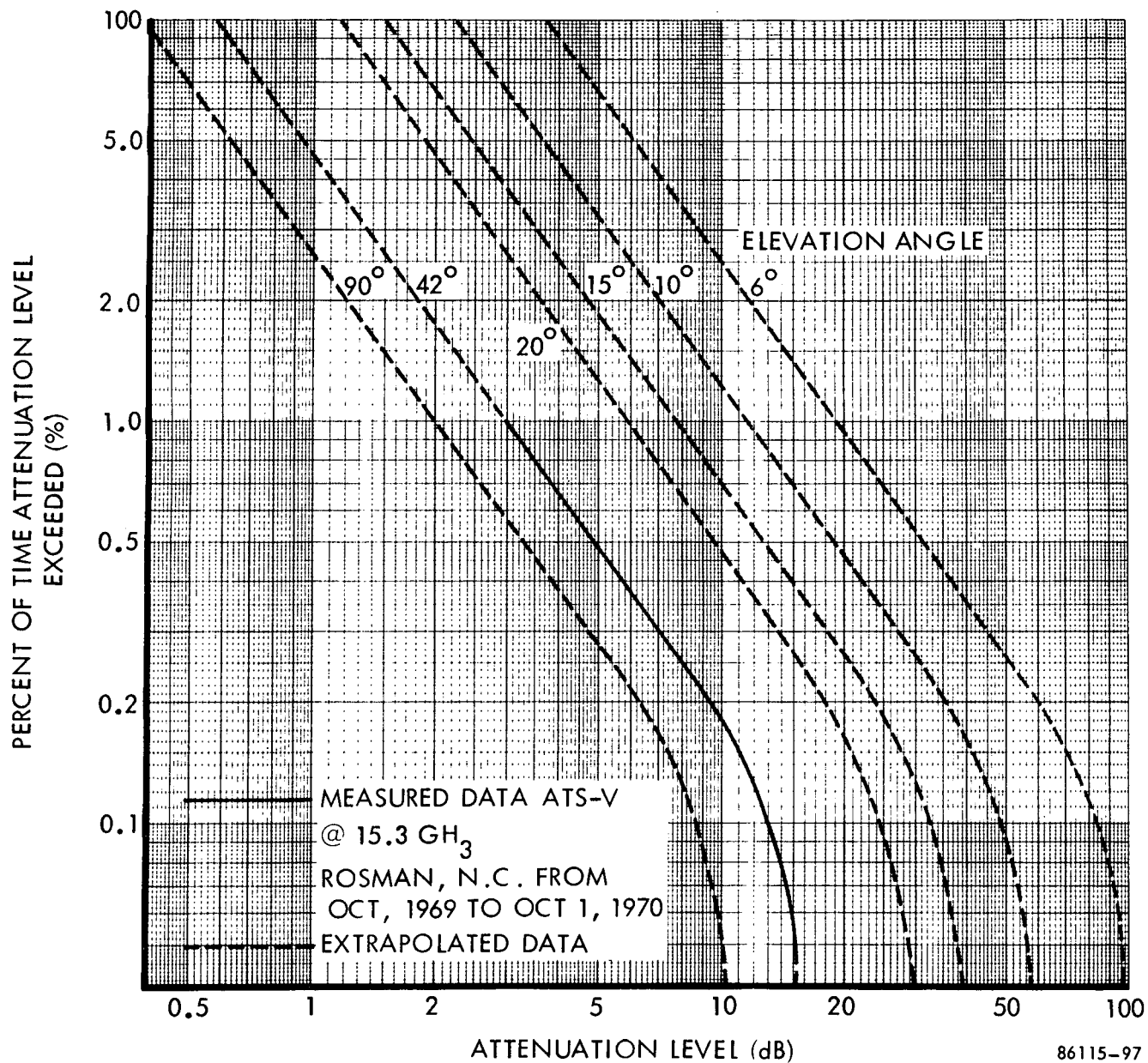


Figure 3.4.3.1-5. Data Extrapolated from the ATS-V
Measured Propagation Data

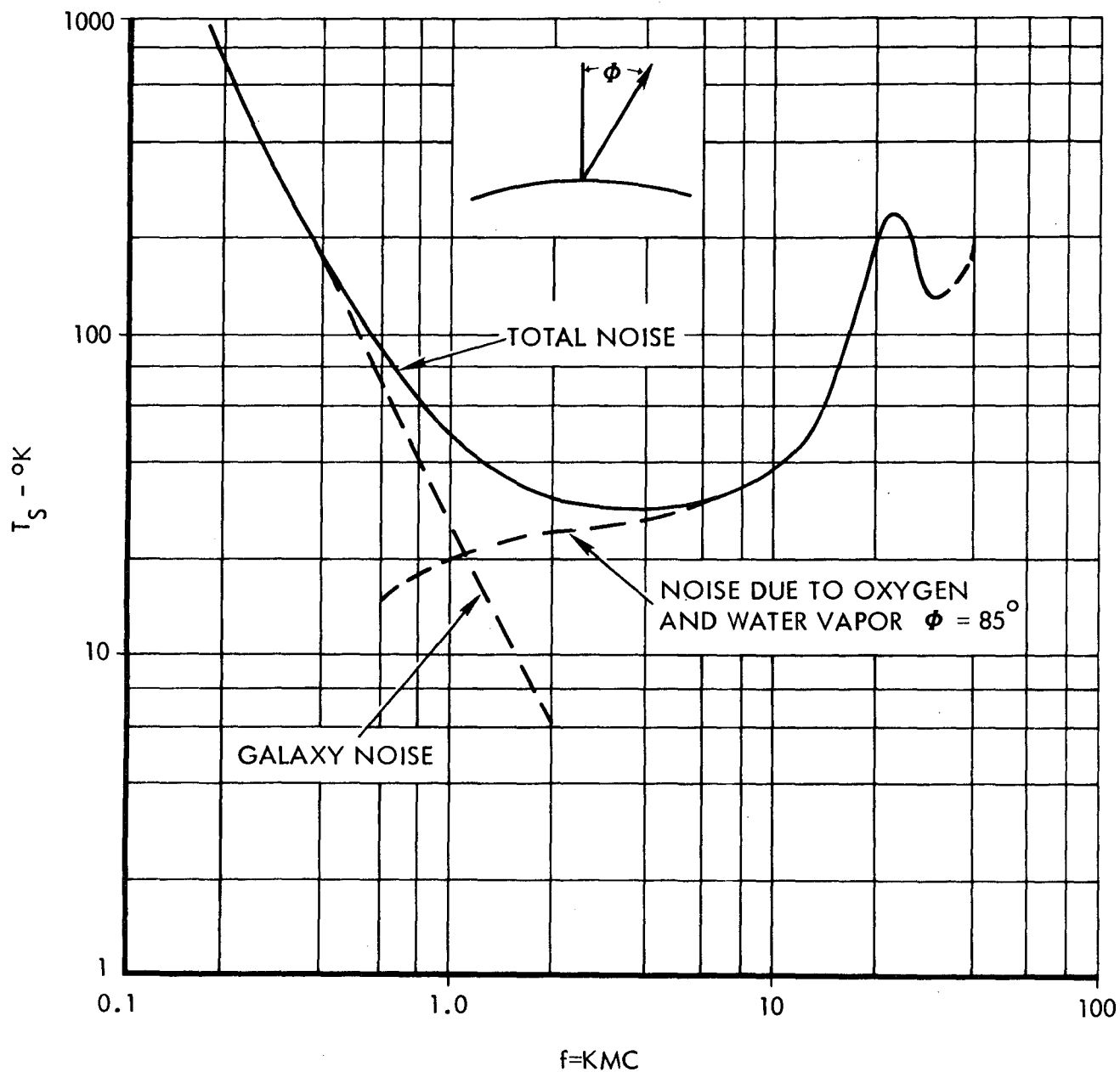
3.4.3.2 Noise

The effects of all sources of noise are implicitly included in the receiving system noise temperature T . However, in order to determine this system noise temperature and to evaluate its frequency dependence, the various noise sources require individual consideration. The primary contributors to a system noise temperature are the preamplifier noise temperature (which is directly related to the noise figure) and the antenna noise temperature. The network between the antenna and preamplifier also contributes to the overall noise temperature but proper design will make these effects secondary. Preamplifier noise figures, and their associated frequency dependence, are addressed in Sections 6.3 and 7.2. Therefore, the discussion which follows will be primarily concerned with the contributors to antenna noise temperature. An earth based receiving system is assumed. Under this assumption the principal noise sources which influence the effective antenna temperature are the cosmos (of which our own galaxy is the predominant source), the sun, the atmosphere (troposphere), and the earth itself.

These noise sources are each frequency dependent, but when their combined effects are considered an attractive "window" exists in the 1-10 GHz frequency band thus providing some inducement for operating in this region. This phenomenon is illustrated in Figure 3.4.3.2-1, which demonstrates the inverse dependence of galactic noise and direct proportionality of atmospheric effects with frequency in the microwave band. This figure provides a baseline only since galactic noise can vary over a wide range depending upon relative location of the galactic center and antenna boresight. Additionally, the effect of the sun can produce variations in the sky noise temperature as discussed extensively in Reference [7]. The ground noise contribution (not considered in Figure 3.4.3.2-1) to antenna noise temperature can be made very low by keeping the minor sidelobes low in amplitude, but in any eventuality is essentially constant with frequency over the assumed range.

Using nominal values for cosmic noise, assuming a sun temperature ten times the quiet level, average values of atmospheric absorption, and a ground noise contribution of 36°K , a composite temperature curve, representing the noise temperature of a typical directive antenna can be computed, as shown in Figure 3.4.3.2-2. This curve is approximately applicable to any moderately directive antenna, since antenna temperature (averaged over all directions) does not depend directly upon antenna gain and beamwidth. The dashed curves in Figure 3.4.3.2-2 indicate the maximum and minimum levels of cosmic and atmospheric noise likely to be observed, and the solid curves represent a nominal value of antenna temperature with the beam elevation angle as a parameter.

It is of interest to mention some published values which indicate the state-of-art in low noise antenna design. Bell Telephone Laboratories personnel



85306-3

Figure 3.4.3.2-1. Sky Noise Temp. Due to Galactic Sources

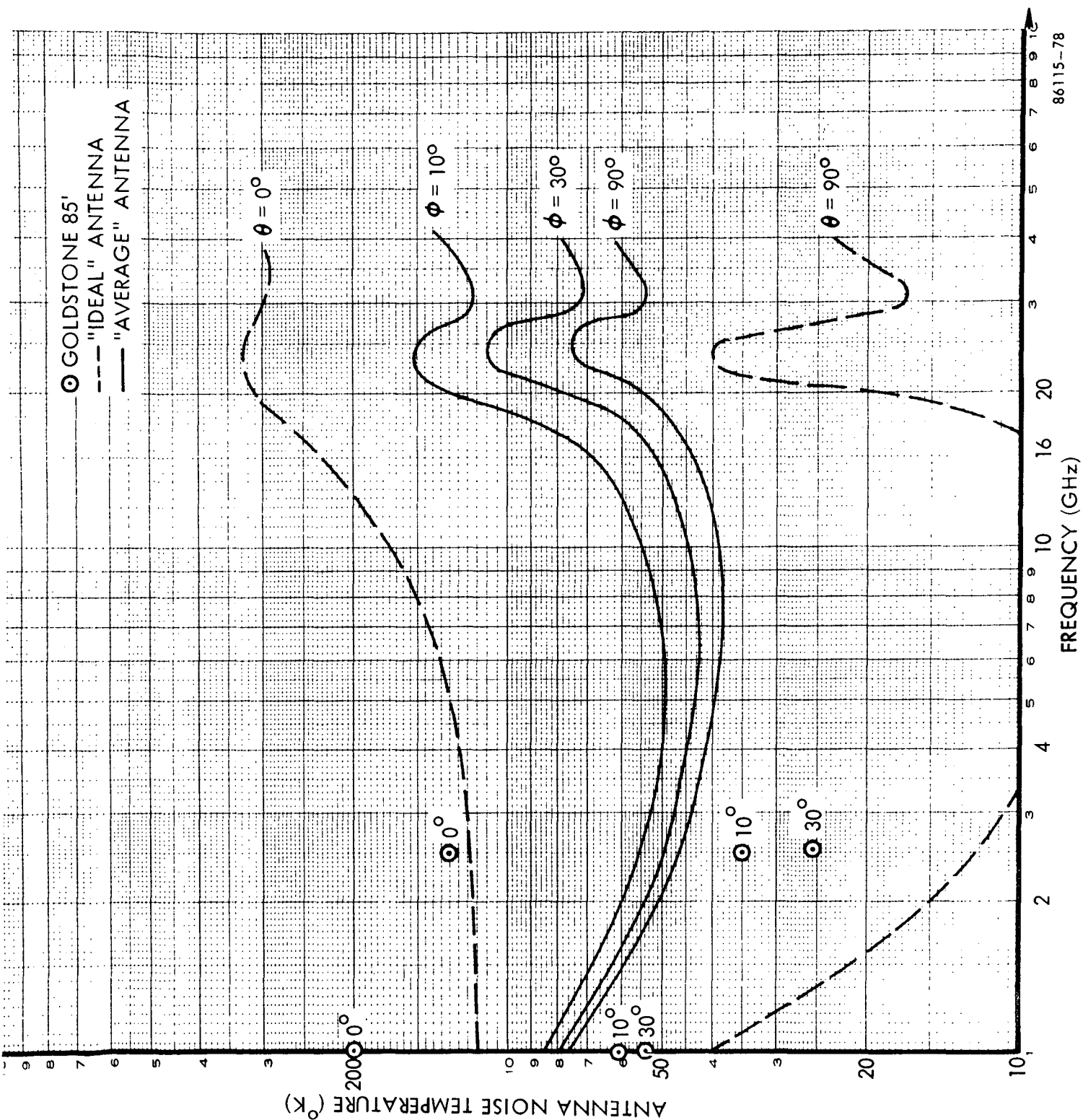


Figure 3.4.3.2-2. Antenna Noise Temperature for Typical Conditions of Cosmic, Solar, Atmospheric, and Ground Noise

have reported an antenna temperature of about 6° K with the antenna pointed vertically for a horn reflector type antenna at 5.65 GHz. The JPL group at Goldstone have reported an antenna temperature of 15° K with a parabolic reflector at 2.388 GHz. Thus, these results indicate that antenna temperatures can be made to approach low values, if this is required.

Noise temperatures which will be possible for state-of-the-art preamplifiers in the time frame of interest are indicated in Figures 3.4.3.2-3 and 3.4.3.2-4. These projections are based primarily upon technology predictions recently performed by Radiation and reported in Reference [18]. While possible, achievement of these noise temperatures may not represent a cost effective solution in all cases. Thus preamplifier noise figures are considered individually when subsystem descriptions and costs are examined. However, since system noise temperature is approximated by the sum of antenna and preamplifier temperatures in the absence of coupling losses, the data in this section provides a reasonable insight into the system noise density to be encountered.

3.4.3.3 Other Performance Factors

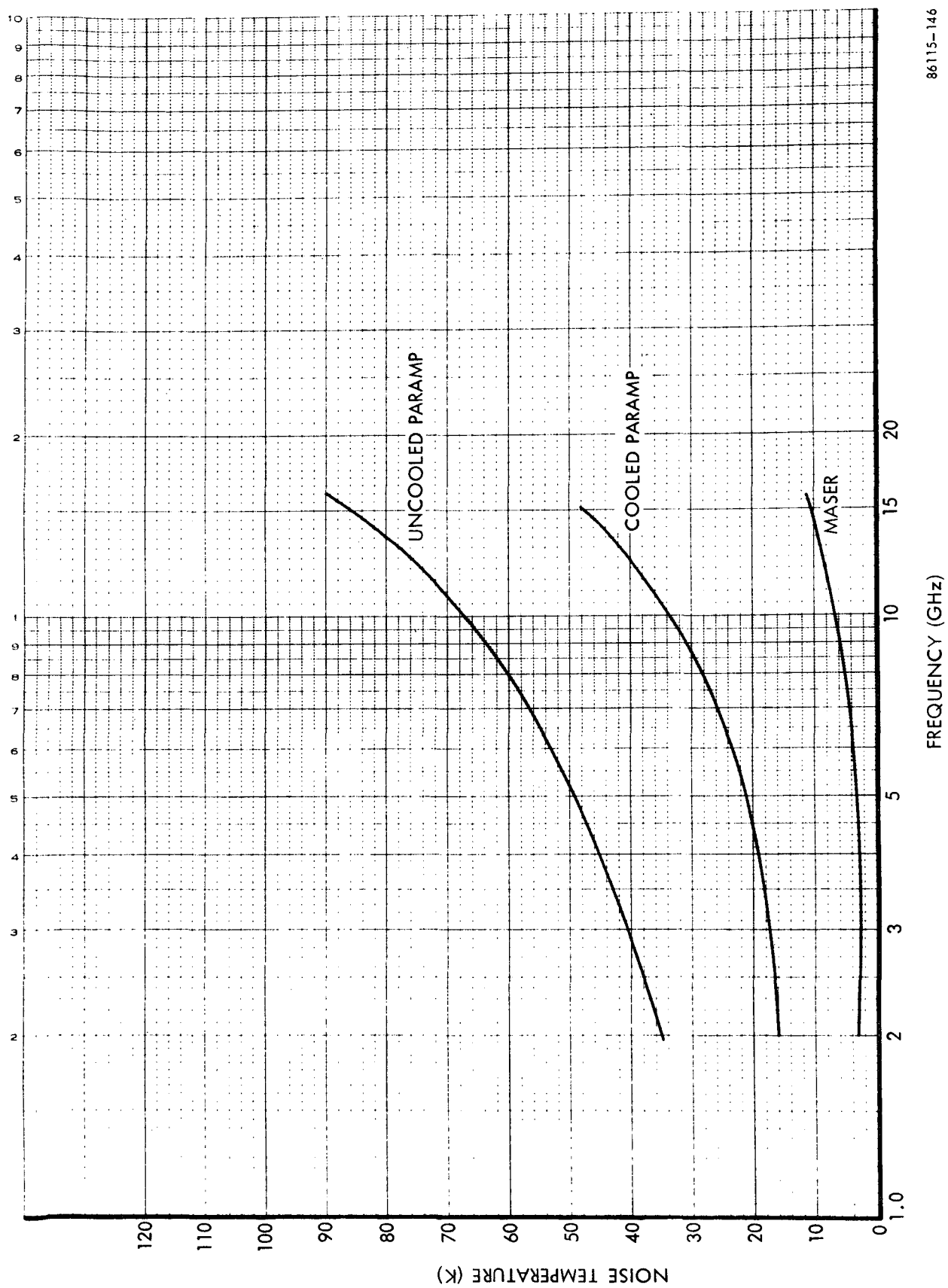
Several frequency dependent phenomena exist which have not been previously discussed but must be included for evaluation since they directly affect the system performance. The most relevant of these phenomena are RFI and EMI (including all man-made noise) with such things as multipath and anomalous propagation conditions requiring recognition. Atmospheric noise, as produced by lightening, etc., is not a predominant factor in the 1-10 GHz band or above.

The amplitude of man-made noise decreases with increasing frequency and varies considerably with location. It is chiefly due to electric motors, neon signs, power lines, and ignition systems, thus, the effects are much more significant in urban areas. In quieter remote locations the noise level from man-made sources will usually be below galactic noise in the microwave frequency range.

RFI is a potential problem for the required communication network and will be especially so in the 1975-80 time frame. RFI predictions are alarming and with increasing spectral usage by commercial and military satellite communication systems, land-based microwave links, and other space missions this aspect of the problem is a major factor in frequency selection. For this reason a dedicated clear channel is very desirable. Certainly a site survey should be performed prior to final selection of locations for the ground stations.

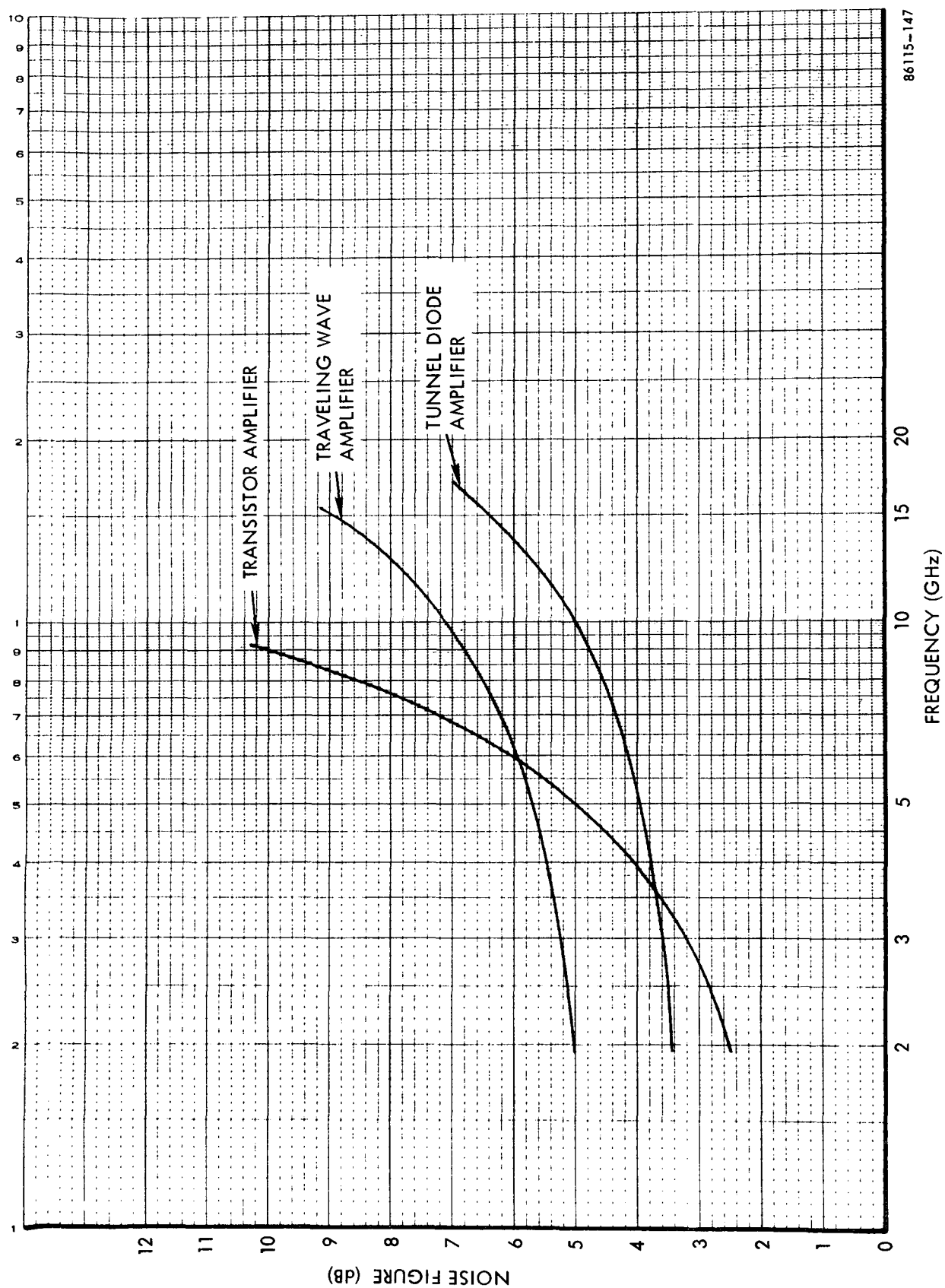
3.4.4 Component Availability

Since the primary result required of the study effort is a cost effective ground station approach for the various users hypothesized, emphasis must be placed upon off-the-shelf hardware and proven techniques. Thus, constraints are imposed



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Figure 3.4.3.2-3. Projected Maser and Paramp Noise Temperatures



86115-147

Figure 3.4.3.2-4. Projected TWT, TDA, and Transistor Noise Figures

upon both ends of the link. As illustrated in Section 4.0 of this report, this philosophy should be possible and link requirements do not push state-of-the-art if the 21 - 22 GHz carrier frequency can be avoided. In addition to RF equipment for the 21 - 22 GHz frequency, a high rate data recorder presents a potential problem. High data rate demods, bit synchronizers, etc. will probably be available off-the-shelf or nearly so in the time frame of interest.

Specifics related to hardware availability are discussed further throughout this report and in Appendix A.

4.0 SYSTEM ANALYSIS

The analyses performed in defining both the Regional Collection Center and Local User Terminals is summarized here. Since the two systems are rather independent and dedicated transmission systems are assumed, the two can be analyzed separately. The spacecraft systems to accommodate this are discussed in Section 5.0 and other related information is found in the appendices.

Discussion of the Regional Center and local terminals is found in Sections 4.1 and 4.2, respectively.

4.1 Regional Collection Center (RCC)

Analyses and trade-offs which have been performed relative to definition of the Regional Collection Center are summarized in this section of the report. The discussion is concluded by a summary of the baseline system parameters. Additional detail, specifically, subsystem descriptions and cost estimates, is found in Section 6.0.

4.1.1 Guidelines and Assumptions

The Regional Collection Center, also described as the Mode I Terminal, is designed for the majority of users. This facility or facilities will receive and record the bulk of data generated and transmitted by the satellites. The Regional Collection Centers will be designed to accommodate the maximum data rates imposed on the RF downlink. The Centers will perform only minimal processing with the plan of forwarding data to other facilities for any extensive processing and eventual dissemination to the users. The Centers may also perform commanding functions to control the satellites, but this is a separate function and not considered as part of the DRGS Study. The primary users of the earth resources data will be the sponsoring agencies such as NASA/GSFC, Department of Agriculture, Department of the Interior, etc. These agencies will influence the operation of the Centers and, accordingly, the operation of the satellites.

NASA/GSFC has provided guidelines for the study effort by placing limits on a number of system parameters of interest. For the Regional Collection Center, these bounds and supporting rationale are summarized below.

The data rate should range between a minimum of 60 Mb/s and a maximum of 200 Mb/s. The rate is a function of the quantization levels, scanning rate, coverage pattern, and number of spectral bands of the primary data source; these relationships

are discussed in Section 3.2. It was expected initially and verified during the study effort that the ground data recorder would be one of the critical hardware elements in determining the implementation ease for the higher data rates of interest.

Digital transmission is implicitly assumed. While an argument can be made for an analog system on the basis of signal-to-noise ratio, recorder complexity, etc., accuracy requirements imposed dictate a digital system. As discussed in Section 4.1.2, TDM is an attractive alternative for a digital system.

A bit error rate (BER) of one bit error in each 10^6 bits received is taken as a design goal. Equivalently, the probability of error for each bit is 10^{-6} .

A directional antenna is initially assumed for the satellite for the Regional Collection Center link. A beamwidth on the order of 5° is reasonable based upon pointing requirements and the expected orbit accuracy. An onboard computer will be utilized to provide program tracking. This 5° beamwidth corresponds to an antenna gain of 30 dB. The analysis verifies that this approach is both feasible and desirable.

The spacecraft prime power available for the Mode I communication system is taken as 30-40 watts nominal, with a maximum available power of 100 watts.

Initially, a carrier frequency in the 15 GHz range was deemed necessary because of allocations expected. As a consequence, the more detailed system analysis has been performed for a carrier frequency of 15.25 GHz. However, recent ITU actions indicate that operation at a frequency as low as 8.5 GHz may be possible or as high as 21.2 GHz may be required. Accordingly, the impact of these frequency extremes has been considered.

The Regional Center should provide operation to the maximum feasible range. Accordingly, the ground system should be designed to operate to a minimum elevation angle of 5° . The system can tolerate a nominal percent (1-5%) outage due to precipitation. However, this implies reduced coverage corresponding to greater minimum elevation angles instead of total inoperability during periods of rainfall.

4.1.2 Modulation/Multiplexing Considerations

There are numerous ways of transmitting the information from the sensors to the earth, and several trade-offs are associated with the choice of a modulation/multiplexing technique. These techniques range all the way from a purely time multiplexed, high rate system to a purely frequency multiplexed system in which each channel is transmitted to the ground on a separate carrier. The trade-offs lie in the areas of cost and complexity of the ground station, bandwidth occupancy, and complexity of the spacecraft equipment. In the following paragraphs, a number of techniques and their advantages and disadvantages will be discussed. Additional consideration of specific modulation techniques (i.e., PSK vs FSK) is found in Appendix A.

Three prime techniques are considered for transmitting the information from the several sensors to the Mode I terminal. These are time division multiplexing with a single RF carrier and two forms of frequency division multiplexing -- one with modulation of each digitized sensor channel onto a separate RF carrier and the other with modulation of each digitized sensor channel onto a separate subcarrier with subsequent modulation of the composite of these onto a RF carrier. Each of these is discussed in the following sections where a total data rate of 180 Mb/s, corresponding to 6 individual signals at 30 Mb/s each, is assumed for comparative purposes.

In addition to the three techniques described above, a hybrid analog-digital technique was also considered and the results are shown in this section.

4.1.2.1 Time Multiplexed System

By time multiplexing the data from all the sensor channels, a high rate bit stream is generated which is then transmitted to the ground by bi-phase or quadri-phase modulating the carrier. The resulting spectrum has the shape shown in Figure 4.1.2.1-1; the width between the first zeros is equal to twice the bit rate in the case of bi-phase modulation and equal to the bit rate in the case of quadri-phase modulation. In both cases approximately 90% of the total signal energy is contained within the first zeros of the spectrum, and filtering would be required in order to limit the total bandwidth occupied. The filtering causes a degradation in performance because of the resulting inter-symbol interference.

The carrier-to-noise density ratio (C/kT) required to achieve the specified 10^{-6} bit error probability is given by

$$C/kT = R \cdot \frac{E_b}{N_o} \quad \left| \quad P_e = 10^{-6} \right.$$

where R is the bit rate and E_b/N_o is the signal-to-noise ratio in the bit rate bandwidth.

For $P_e = 10^{-6}$, the theoretical $E_b/N_o = 10.5$ dB for both bi-phase and quadri-phase modulation. Assuming 2 dB degradation due to the bit demodulator and bit synchronizer, one finds for $R = 180$ Mb/s

$$C/kT = 82.5 + 12.5 = 95 \text{ dB-Hz}$$

The purely time multiplexed system results in a relatively simple spacecraft design except, possibly, for the multiplexer. It is most likely that quadri-phase modulation would be used in order to efficiently utilize the frequency spectrum. A potential drawback of this system is that each ground station must demodulate the entire RF spectrum in order to obtain any

video information. A high rate bit demodulator and bit synchronizer followed by a decommutator (demultiplexer) are required, and it is almost as simple to have all channels available simultaneously as it is to select only a few channels at a time. The building block concept can be applied to the recording equipment and this offers substantial cost savings to a user interested in a limited number of sensor bands. However, this is a secondary consideration and TDM compares very favorably otherwise.

BI-PHASE MODULATION:

$$F_+ = F_c + R$$

$$F_- = F_c - R$$

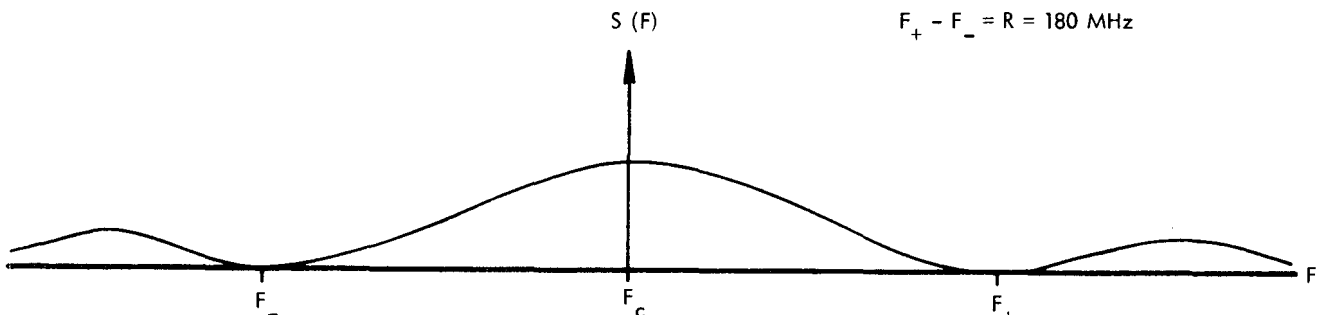
$$F_+ - F_- = 2R = 360 \text{ MHz}$$

QUADRI-PHASE MODULATION:

$$F_+ = F_c + R/2$$

$$F_- = F_c - R/2$$

$$F_+ - F_- = R = 180 \text{ MHz}$$



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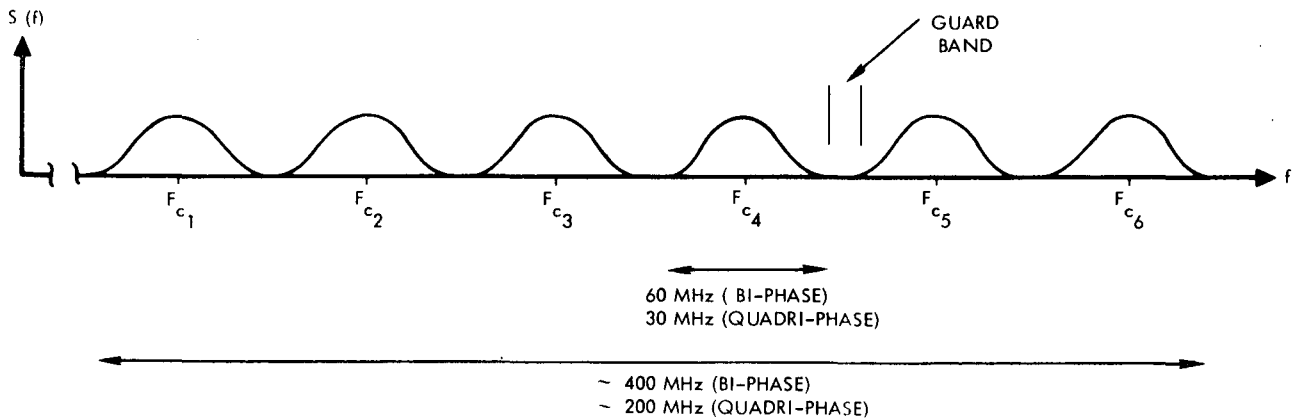
Figure 4.1.2.1-1. Frequency Spectrum (Time Multiplexed System)

It should be added that demodulators and bit synchronizers operating at a 200 Mb/s rate are not yet available off-the-shelf; however, development is being carried out in many places, and implementation in the 1973-75 era is expected to be relatively straightforward. [20,21]

4.1.2.2 Frequency Multiplexed Systems

The system wherein each group of twelve channels is time multiplexed and transmitted on a separate carrier, lies at the opposite end of the range of possibilities.

Either bi-phase or quadri-phase modulation could be used in addition to other techniques; filtering of the modulated carriers is mandatory in order to avoid interference between adjacent groups of channels. The resulting frequency spectrum is shown in Figure 4.1.2.2-1.



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Figure 4.1.2.2-1. Frequency Spectrum
(Frequency Multiplexed System)

The C/kT ratio for each group of channels is computed as in the previous section, but with the bit rate being that corresponding to a single spectral band (30 Mb/s). For $P_e = 10^{-6}$ and $R = 30$ Mb/s, a C/kT of 87.2 dB-Hz is required for each group of channels. This is 7.8 dB lower than for the purely time multiplexed system; however, assuming the total spacecraft ERP to be the same in both cases, the ERP per carrier will also be reduced by 7.8 dB (not considering implementation losses), and the ground station sensitivity required is the same.

Implementation of the spacecraft portion of the frequency multiplexed system appears to be rather difficult for several reasons. Six oscillators would be required to generate the carrier frequencies, and each carrier would require a filter in order to avoid inter-channel interference. Most likely, guard bands would be required, resulting in less efficient use of the frequency spectrum. Another problem is the combination of the individual channels at the transmitter; unless a non-saturating amplifier is used, the carriers have to be combined at high power in order to be transmitted via the same spacecraft antenna. Due to the close frequency spacing of the individual groups of channels, frequency-selective devices might not be able to provide enough isolation between the channels, and hybrids might have to be used for combining, resulting in a 9 dB power loss for each channel*

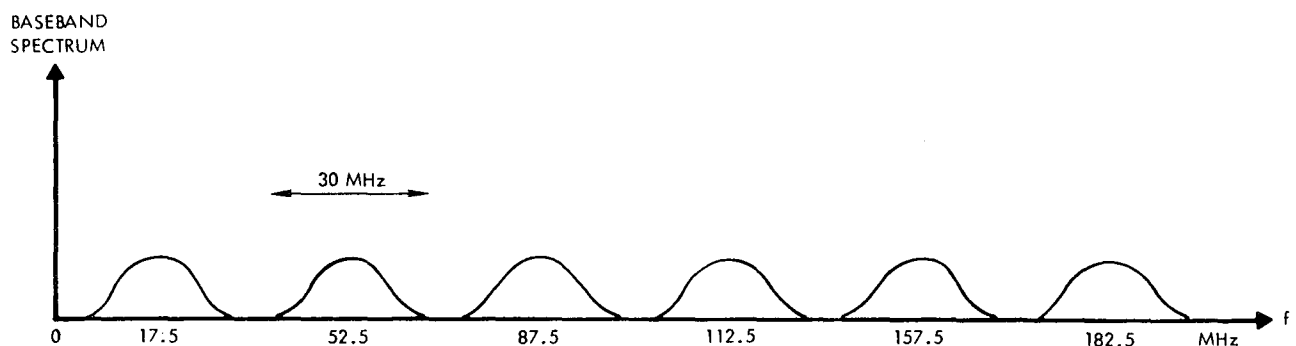
* The 9 dB figure applies to the combination of eight channels; six channels could be combined in such a way that only four of the channels suffer a 9 dB loss, with the other two channels suffering only a 6 dB loss.

The frequency multiplexed system permits a user who is interested only in one spectral band to get by with a narrowband (30–60 MHz bandwidth) preamplifier and medium rate (30 Mb/s) digital equipment. However, the required system sensitivity (as measured by G/T , the ratio of antenna gain to receiving system noise temperature) is the same as in the case of the purely time multiplexed system and may, in fact, be higher because of the losses in combining the carriers at the spacecraft and/or reduced transmitter efficiency due to operation in a linear mode.

4.1.2.3 Angle Modulation Using Subcarriers

A commonly used technique to avoid the problem of combining the signals from the different groups of channels at high power levels is to modulate different subcarriers by the individual groups of channels, with the composite baseband phase or frequency modulating the carrier. This technique permits combining the signals from the individual groups of channels at low power, and the angle modulated carrier is not affected by a saturating power amplifier. The penalties are less efficient use of the frequency spectrum and an increase in the receiver sensitivity required to meet the specified bit error performance.

A typical baseband spectrum when quadri-phase modulation is used for the subcarriers is shown in Figure 4.1.2.3-1. Filtering of the carriers is again required in order to avoid interchannel interference.



85764 26

Figure 4.1.2.3-1. Baseband Spectrum for Subcarrier Approach

In a system using subcarriers, each ground station requires one wide-band preamplifier and one wideband detector, plus a subcarrier detector, bit synchronizer, and demodulator for each spectral band or channel desired.

Phase modulated systems using subcarriers, such as USB or SGLS, have been operational for some time and are well known. A phase-lock loop at the receiver tracks the residual carrier, and the individual subcarriers are "stripped off" by mixing the incoming signal with this locally generated carrier reference and bandpass filtering. Since this method of demodulation is not optimum, the receiver sensitivity is decreased. The "modulation loss" for the m -th channel is given by [22]

$$L_m = 10 \log \left[2J_1^2(\beta_m) \cdot \prod_{\substack{k=1 \\ k \neq m}}^M J_0^2(\beta_k) \right] .$$

For six equal level subcarriers, the optimum phase deviation β minimizing the modulation loss is 0.58 radians. The corresponding modulation loss is 11.8 dB; i.e., the C/kT required for the same bit error performed would be 11.8 dB higher than the 87.2 dB determined in Section 4.1.2.2. This corresponds to a 4 dB increase in the required system G/T . It should also be noted that, in addition to the modulation loss, the carrier demodulator produces interchannel interference which further degrades performance. It can therefore be concluded that the use of phase modulation is unlikely to result in an acceptable system for the present application.

Alternatively, the carrier can be frequency modulated by the composite baseband. Since the composite baseband is approximately 200 MHz wide (assuming quadri-phase modulated subcarriers), the frequency deviation cannot be chosen too large in order to conserve frequency spectrum. For a peak deviation of 200 MHz, the approximate bandwidth of the modulated carrier is found by Carson's rule:

$$B_{RF} = 2 \cdot (f_m + \Delta f) = 800 \text{ MHz}$$

where f_m is the highest modulating frequency and Δf is the peak frequency deviation.

The signal-to-noise ratio at the output of the FM demodulator is given by

$$(S/N)_o = 3 \left(\frac{\Delta f}{f_m} \right)^2 \cdot \frac{B_{IF}}{2f_m} \quad (S/N)_{IF} = 3 \left(\frac{\Delta f}{f_m} \right)^2 \cdot \frac{1}{2f_m} \cdot C/kT$$

where $(S/N)_{IF}$ is the signal-to-noise ratio measured in the IF bandwidth B_{IF} . Because of the parabolic noise spectrum at the FM demodulator output, the signal-to-noise ratio is not the same for all channels; for the M -th channel is given by:

$$(S/N)_m = \frac{3M^2}{1+3m(m-1)} \cdot \left(\frac{\Delta f}{f_m} \right) \cdot \frac{1}{2f_m} \cdot C/kT$$

where M is the total number of channels ($M = 6$ in the case at hand). In order to obtain a bit error probability of 10^{-6} in the top channel (having the worst performance), the C/kT ratio required is found to be 98.2 dB-Hz from the above expression. The proper use of pre-emphasis results in nearly equal signal-to-noise ratios in all six channels and reduces the required C/kT ratio.

Implementation of the frequency modulated system requires a wideband linear VCO (voltage controlled oscillator) at the spacecraft and a wideband discriminator at the ground station. At present, VCO's capable of accepting a 200 MHz modulating signal are beyond the state-of-the-art (present state-of-the-art is approximately 100 MHz); on the other hand, wideband discriminators using transmission lines of different length can be implemented without too much difficulty. Implementation of both VCO and discriminator becomes easier as the carrier frequency is increased.

4.1.2.4 Summary of Digital Multiplexing Techniques

The results of the preceding sections are summarized in Table 4.1.2.4 where the advantages and disadvantages of the three prime modulation/multiplexing techniques are indicated. As indicated, TDM is the favored technique unless high rate spacecraft hardware proves to present unexpected complexity and cost.

4.1.2.5 Analog Multiplexing Techniques

Multiplexing techniques which allow the transmission of the sensor outputs to the ground stations in analog form, or a hybrid form of analog and digital, are also possible. Although the baseline requirement is for a digital system, two specific analog types are considered because of potential advantages of an analog system.

The two types considered are; (1) the conventional form of frequency division multiplexing of the individual analog channels onto low frequency subcarriers and frequency modulation of the resulting composite baseband onto an RF carrier, and (2) a hybrid, or mixed base, technique in which the sensor channels are sampled and quantized with the quantizing error transmitted in the amplitude of a pulse included in the sequence of data pulses.

4.1.2.5.1 FDM/FM

In analog frequency division multiplexing, if a 200 kHz bandwidth per sensor channel is assumed (corresponding to a 2.4 Mb/s rate when sampling at the Nyquist rate and using 6-bit quantization), the width of the baseband signal is approximately 15 MHz, well within the state-of-the-art for FM modulators. A comparison

Table 4.1.2.4. Comparison of Digital Multiplexing Techniques

Technique	Advantages	Disadvantages
<ul style="list-style-type: none"> Time Division Multiplexing 	<ul style="list-style-type: none"> Lowest required C/kT Lowest total bandwidth Minimum RF complexity 	<ul style="list-style-type: none"> Extraction of partial data requires complete high-bit-rate demultiplexing Significant S/C power requirements for high-bit-rate multiplexing New development may be required for high-bit-rate implementation
<ul style="list-style-type: none"> Frequency Division Multiplexing (Separate RF carriers for each channel) 	<ul style="list-style-type: none"> Modular Approach Partial data can be extracted without demultiplexing systems available Lower power requirements for S/C multiplexing system 	<ul style="list-style-type: none"> Complex S/C RF implementation Potential significant RF power losses in channel combining in S/C Potential interchannel interference Inefficient use of RF spectrum Full complement of demultiplexing equipment required for each channel
<ul style="list-style-type: none"> Frequency Division Multiplexing (Separate subcarriers for each channel) 	<ul style="list-style-type: none"> Less complex RF implementation Partial data can be extracted without demultiplexing all data Relative ease in combining channels at subcarrier frequencies 	<ul style="list-style-type: none"> Highest required C/kT Inefficient use of RF spectrum New development required for wideband linear VCO Potential for interchannel interference

(reference Figure 4.1.2.5.1-1) indicates that a video signal-to-noise equivalent to 6-bit quantization can be achieved by using FM with approximately the same ground station sensitivity and the same RF bandwidth as that for an exclusively time multiplexed system using bi-phase modulation. A potentially big cost advantage might be realized by noting that the bandwidth of each sensor channel corresponds approximately to that of a supergroup (240 kHz) resulting by frequency multiplexing 60 telephone channels. It might therefore be possible to use off-the-shelf telephone demultiplexing equipment at the ground station which would result in considerable cost savings.

The use of FDM/FM techniques results in S/C and ground station complexity approximately the same as for PCM-FDM-FM described in the preceding section. It is especially susceptible to inter-channel interference due to non-linear phase-frequency characteristics for the system components and transmission medium and requires pre-emphasis of the baseband signal to allow nearly equal output signal-to-noise ratios for all channels. For this reason and because of system accuracy requirements, analog FM is not considered a promising approach even though S/N ratios equal to or greater than for digital transmission are attainable.

4.1.2.5.2 Mixed Base Modulation (MBM)

A new proprietary modulation technique has been developed by Radiation called MBM. It offers processing gain without as great a penalty in bandspreading as FM or PCM/PSK. It combines discrete and continuous-base modulation and should be considered for the DRGS application [23]. An example of MBM applied to an image transmission system is shown in Table 4.1.2.5.2 for a 25 MHz video base-bandwidth [24].

Table 4.1.2.5.2

Comparison of FM, PSK, MBM and SSB

Method	SNR Required in IF (For 40 dB SNR out)	Minimum IF BW Required
FM ($\beta = 15$)	23 dB	375 MHz
QPSK	21 dB	350 MHz
MBM	26 dB	50 MHz
SSB	40 dB	25 MHz

It can be seen that MBM offers processing gain only 3 to 5 dB below FM or PSK but requires but one-seventh the bandwidth. In a subcarrier or channelized system, MBM could provide a means for economically supporting a high-rate channel at a reasonable bandwidth.

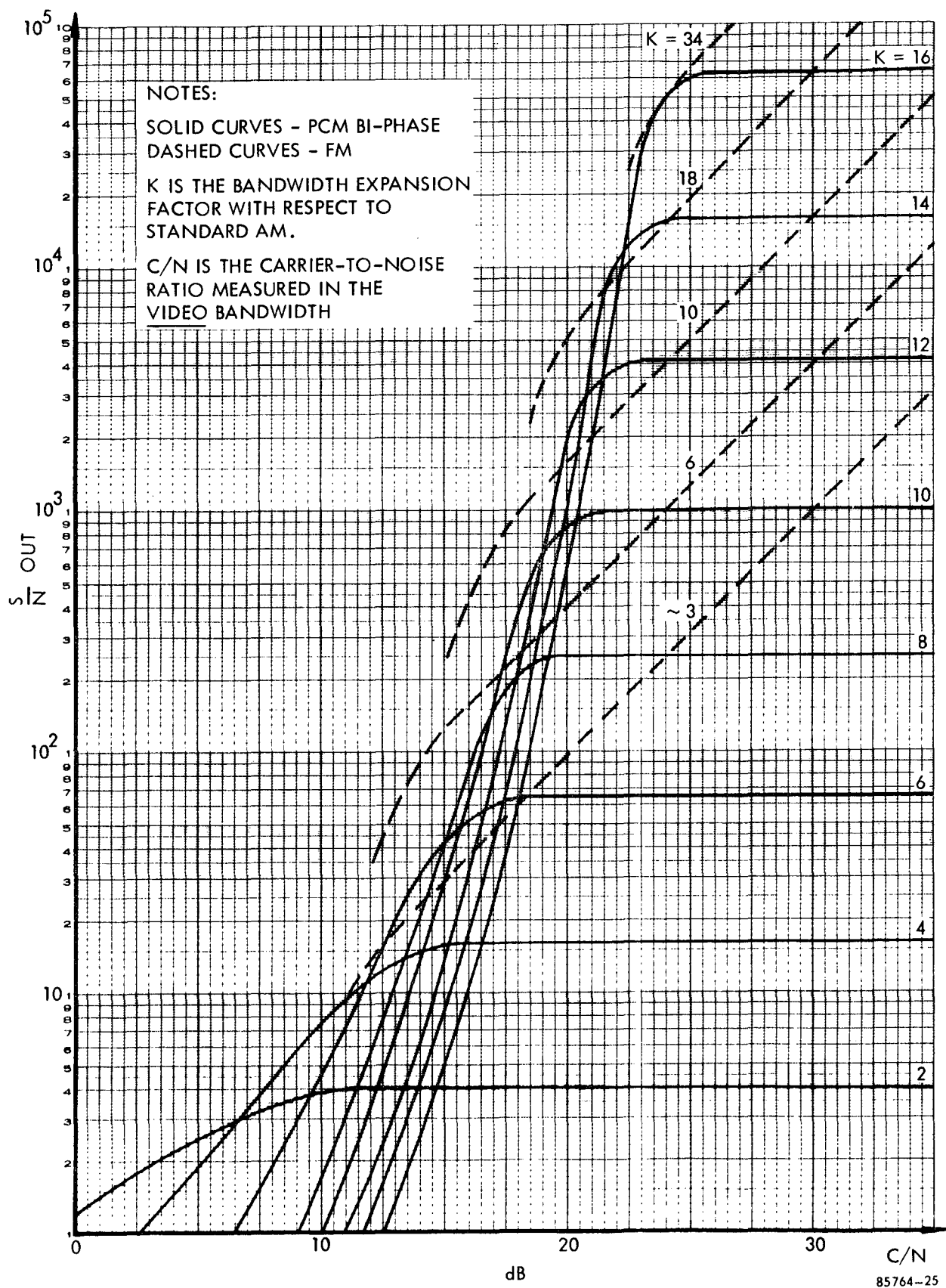


Figure 4.1.2.5.1-1. Comparison between PCM Bi-Phase and Analog FM Systems

4.1.3 Link Analysis

The discussion in this section summarizes the link analysis and link trade-offs leading to definition of parameters for the Regional Collection Center. The analysis has been performed for center frequencies of 8.4, 15.25 and 21.2 GHz. Since the transmit and receive antennas are constant gain and constant aperture respectively, the results are valid for small perturbations in frequency around the values utilized.

It is demonstrated that acceptable system operation can be realized over the full frequency range considered; however, a performance and/or cost penalty will be incurred if 21.2 GHz is utilized.

4.1.3.1 Baseline Link Parameters

Table 4.1.3.1-1 contains a summary of salient link parameters at the three frequencies of interest assuming operation to 5° elevation angle and rain margin adequate for a 4mm/hr. rainfall rate. Perturbations, especially for the 21.2 GHz link, are presented in Section 4.1.3.3.

Table 4.1.3.1-1. Salient Link Parameters

	8.4 GHz	15.25 GHz	21.2 GHz
Transmitter RF Output	10W	10W	5W
Transmitting Antenna Gain	30 dB	30 dB	30 dB
Data Rate	100 Mb/s	100 Mb/s	100 Mb/s
Modulation	PSK or QPSK	PSK or QPSK	PSK or QPSK
Required S/N for 10 ⁻⁶ BER	10.5 dB	10.5 dB	10.5 dB
Minimum Elevation	5°	5°	5°
Rain Margin for 4mm/hr	2.0 dB	9.2 dB	15.3 dB
Operating Margin	8 dB	8 dB	8 dB
System Noise Temp.	395°K	550°K	915°K
Antenna Diameter	6.4'	16.5'	115'

A short explanation of some of these parameters provides additional insight into the analysis. A number of these arise directly from the guidelines given in Section 4.1.1. For example, an output power of 10 watts is achievable by a TWT operating in a saturated mode with approximately 25% efficiency for the two lower frequencies. Such an output power is not presently available off-the-shelf at 21.2 GHz and achievement of even 5 watts represents an expenditure of development dollars. The 30 dB transmit antenna gain is that corresponding to a 5° beamwidth.

A data rate of 100 Mb/s has been utilized in sizing the RF portion of the link. This allows a perturbation by a factor of two in either direction to cover the range of interest. As will be illustrated, the rate can be conveniently increased to 200 Mb/s at the two lower frequencies at little cost impact.

Coherent PSK is assumed for computing the required signal-to-noise ratios. Use of QPSK results in a bandwidth savings but does not affect the link computations.

The rainfall margin is derived as discussed in Section 3.4.3. The system is sized to provide the specified performance up to a rainfall rate of 4mm/hr. which will provide operability approximately 99% of the time in most areas. This figure can be relaxed to provide a more reasonable (less costly) 21.2 GHz system.

The major contributions to system noise temperature have been discussed in Section 3.4.3. For the baseline link budgets rather conservative estimates have been utilized. As shown in Section 6.3, it should be possible to meet or improve upon the temperatures given in straightforward fashion.

The system noise temperature referenced to the antenna is calculated by:

$$T_S = T_A + (L-1) 290^\circ + LT_R$$

Where T_S = System noise temperature

T_A = Antenna noise temperature due to sky noise

T_R = Receiver noise temperature due to thermal noise

L = Feed and line loss

A breakdown of the baseline system temperatures is provided in Table 4.1.3.1-2 where an uncooled parametric amplifier has been assumed.

Table 4.1.3.1-2. Elements of System Noise Temperature

	8.4 GHz	15.25 GHz	21.2 GHz
T_A ($^{\circ}\text{K}$)	80	125	210
T_R ($^{\circ}\text{K}$)	250	350	500
L (dB)	.5	.5	1.0
T_S ($^{\circ}\text{K}$)	395	550	915
kT_s (dBm/Hz)	-172.8	-171.2	-169

An operating margin of 8 dB is given. This figure consists of the normal 6 dB, which is a good initial design margin and should be utilized, if feasible, plus a 2 dB hardware implementation loss for the PSK demodulator, bit synchronizer, etc. This represents a reasonable bridge between theoretical performance and practice.

4.1.3.2 Link Budgets

Link budgets for the three frequencies of interest are provided in Table 4.1.3.2-1. The constraint in these budgets is that equivalent performance be provided at each frequency. It is seen that this constraint results in an unrealistic antenna size for 21.2 GHz for the degree of rain margin provided and operation to a 5° elevation angle. The antenna sizes/gains required to achieve the specified performance at the two lower frequencies are quite acceptable. In fact, the sizes are smaller than intuitively expected and are a consequence of utilization of the high gain antenna aboard the satellite. This appears to be a desirable approach for the expected situation in which there are several of the subject ground stations throughout the world. Under a different assumption wherein only one or two ground stations are to be considered, a tradeoff between ground and satellite antenna gain is indicated.

Table 4.1.3.2-1. Link Budgets for 5° Antenna Elevation Angle

	8.4 GHz	15.25 GHz	21.2 GHz
Transmitter Power (dBm)	40	40	37
Line Loss (dB)	1	1	1
S/C Antenna Gain (dB)	30	30	30
ERP (dBm)	69	69	66
Free Space Loss (dB)	180.6	185.7	188.6
Atmospheric Attenuation (dB)	.6	1.4	6.5
Rainfall Attenuation @ 4mm/hr. (dB)	7.0	9.2	15.3
Pointing & Tracking Loss (dB)	1.0	1.0	1.5
Total Losses (dB)	184.2	197.3	211.9
Noise Temp. for Uncooled Paramp (°K)	395	550	915
Noise Density (dBm/Hz)	-172.8	-171.2	-169
C/kT for 0 dB gain Antenna (dB-Hz)	57.6	42.9	23.1
*C/kT required for 10 ⁻⁶ BER @ 100 Mb/s	98.5	98.5	98.5
Required Antenna Gain (dB)	40.9	55.6	75.4
Antenna Diameter (Feet)	6.0	16.5	115

* See Table 4.1.3.2-2

The carrier-to-noise density ratio (C/kT) required to provide the desired performance is derived as shown in Table 4.1.3.2-2. Coherent PSK is assumed and the requirements are based on a data rate of 100 Mb/s. A hardware implementation loss of 2 dB is allowed along with the nominal 6 dB operating margin.

Table 4.1.3.2-2. C/kT Required for 10^{-6} BER

S/N for 10^{-6} BER and Coherent PSK	10.5 dB
Implementation Loss	2.0 dB
Link Operating Margin	6.0 dB
Bandwidth Factor for 100 Mb/s	<u>80.0 dB-Hz</u>
Required C/kT	98.5 dB-Hz

The system as presented has been configured for specific minimum elevation angles and rainfall rates. It is of importance to consider the effect of variations in these parameters and this is done below. Trade-offs and potential perturbations in the system configuration are analyzed in Section 4.1.3.3.

The effect of increasing the minimum antenna elevation angle to 10° is illustrated by the parameters in Table 4.1.3.2-3. The result is a net increase in the link margin available for the systems sized in Table 4.1.3.2-1 of 1.6, 2.3, and 4.7 dB for the carrier frequencies of 8.4, 15.25 and 21.2 GHz, respectively. This increased link margin available means that the specified performance can be achieved at rainfall rates of up to 10mm/hr. rather than 4mm/hr. Thus, during periods of rainfall exceeding the design goal of 4mm/hr., total operability is not sacrificed. Instead operation is constrained to greater elevation angles. As a consequence, a small percentage of coverage is lost for most passes. For example, as shown in Section 3.2, contact time is reduced by approximately 2 minutes as a result of increasing the minimum elevation angle from 5° to 10° . Total contact time exceeding 10 minutes is available for any pass with a maximum elevation angle greater than 30° which means that reasonable operation can be maintained even in precipitation which exceeds the design limits.

Table 4.1.3.2-3. Link Parameters for 10° Antenna Elevation Angle

	8.4 GHz	15.25 GHz	21.1 GHz
Free Space Loss (dB)	179.4	184.5	187.4
Atmospheric Attenuation (dB)	.3	.8	3.3
System Noise Temp. ($^{\circ}$ K)	<u>370</u>	<u>495</u>	<u>845</u>
Net Change in Link Margin (dB)	1.6	2.3	4.7
Rain Margin Available at 5° (dB)	<u>2.0</u>	<u>9.2</u>	<u>15.3</u>
Rain Margin Available at 10° (dB)	3.6	11.5	20.0

As discussed in Section 3.4.3, 1mm/hr. represents a reasonable pre-precipitation rate which will be exceeded less than 3-5% of the time in most climates and therefore is acceptable as a minimum rate for design purposes. Such a change has significant impact on system configuration since rainfall attenuation at 1mm/hr. is only 0.3, 1.7, and 3.4 dB at 8.4, 15.25 and 21.2 GHz, respectively. The attendant antenna diameters which result from this perturbation are 4.6, 7 and 30 feet respectively. Thus, the 21.2 GHz system has become more feasible and operation at the other frequencies is less costly. The budget limited user could well select this alternative.

4.1.3.3 Configuration Trade-Offs

Potential desirable alternative system configurations and parameters are discussed here. Several alternatives are considered including utilization of cooled parametric amplifiers, perturbation in the baseline data rate, more realistic system for 21.2 GHz, utilization of channel encoding, decreases in satellite transmitter power and/or antenna gain, and other related items.

Utilization of Cooled Parametric Amplifiers

Noise temperatures corresponding to the use of uncooled parametric amplifiers were utilized in determination of the required antenna sizes previously. A system approach which results in substantially better performance with the same antenna would be utilization of cooled amplifiers. The improvement in ground station sensitivity achieved by this alternative is indicated in Table 4.1.3.3-1. This improvement can be used to reduce ground antenna size or spacecraft ERP, provide for an increased data rate to 200 Mb/s, provide additional rainfall margin, etc. As shown in Sections 6.3 and 6.4, the cooled parametric amplifier is a cost effective approach for the baseline system.

Table 4.1.3.3-1. System Parameters for Cooled Parametric Amplifier

	8.4 GHz	15.25 GHz	21.2 GHz
Antenna Temperature (°K)	80	125	210
Receiver Temp (°K)	60	70	100
Line/Feed Loss (dB)	.5	.5	1.0
System Temperature (°K)	180	240	410
System Noise Density(dBm/Hz)	-176.1	-174.8	-172.5
Improvement over Uncooled(dB)	3.3	3.6	3.5

As with the analysis for an uncooled preamplifier, the estimates given here are somewhat conservative relative to expected state-of-the-art. An improvement in the system sensitivity of better than 3 dB is available in any event. For the baseline 15 GHz system, this would allow reduction of the antenna diameter from 16.5 feet to 11 feet or an increased data rate to greater than 200 Mb/s.

Perturbation In Data Rate

It is shown above that operation to the maximum data rate of interest can be readily achieved, at least from the standpoint of the RF hardware required. Obviously, the minimum data rate of 60 Mb/s is achieved with comparative ease. The impact of an increased data rate, explored in detail in Sections 6.3 and 6.4, is in terms of complexity and cost of baseband and recording subsystem where hardware to record 200 Mb/s data rates requires considerable improvement/reduction to practice of present day technology.

Realistic 21.2 GHz System

The 115 foot diameter antenna indicated previously for the 21.2 GHz system represents an unacceptable cost for the Regional Center and this situation can be considerably improved as shown below.

Using 2mm/hr. precipitation rate rather than 4mm/hr. as a design goal, a rainfall attenuation margin of 7.2 dB is required at an elevation angle of 5° for a net savings of 8.1 dB. The cooled parametric amplifier yields 3.5 dB for a total improvement of 11.6 dB. Therefore, the required antenna gain becomes 63.8 dB and the attendant antenna diameter is 30 feet. This is a more realistic and acceptable system than previously indicated.

An undesirable result of this reconfiguration is that the inherent flexibility for accommodating the 200 Mb/s data rate has been removed. Now changes in data rate directly impact antenna size with, for example, 200 Mb/s requiring an antenna diameter of approximately 43 feet.

While the system is sized for operation to 5° in 2mm/hr. rainfalls, the specified performance can be achieved in greater precipitation rates via increased elevation angles. For example, for a 10° elevation, adequate margin for 4mm/hr. exists.

The feasibility and complexity of both the satellite and ground equipments providing for transmission and reception of 21.2 GHz is a matter which requires additional study. It is likely that should operation in this frequency band become necessary, special development will be required which will increase system cost accordingly.

Channel Encoding

Channel encoding is a popular and attractive technique to achieve improved link performance at the expense of bandwidth. The normal trade-off is one of power for bandwidth. Coding is most attractive for power shared links where performance is power limited. This is not the situation for the links associated with the Regional Collection Center at least for the two lower carrier frequencies. Because of this fact and the extreme implementation complexity of high rate decoders,* use of channel encoding is not deemed appropriate for the Regional Collection Center links. Should a pressing need develop to conserve link gain, this alternative is open for further consideration. This might happen if, for example, a 200 Mb/s system operating at 21.2 GHz was required or a directional antenna was not used on the satellite. Channel encoding may also be utilized to assure the 10^{-6} BEP through the recorder.

Decreased Satellite ERP

The satellite ERP assumed in the link computations can be decreased directly with improvements in ground station sensitivity or reduced link margin. Conversely, under the stated guidelines, a significant increase in this ERP which would allow reduced ground sensitivity does not appear feasible. While decreased ERP is possible, substantial decreases do not appear attractive because the ground antenna size necessary would increase rapidly and become more expensive. Some savings in transmitter power are allowed by reduced data rate and/or use of cooled parametric amplifiers. This combination results in a potential reduction to 2.5 watts for the 8.4 and 15.25 GHz systems.

As stated in Section 4.1.3.2, the directional antenna appears to be a desirable feature. For example, for the 15.25 GHz system utilization of a fixed earth coverage antenna similar to that designed for ERTS-A would result in a required ground antenna size of over 200 feet diameter. Obviously, this is totally unacceptable. Pointing of the aperture with a 5° beamwidth can be accomplished with proven techniques.

4.1.4 Link Summary

A link analysis has been presented and several trade-offs indicated. It has been shown that the specified performance of 10^{-6} bit error rate is attainable with small to medium sized ground antennas at the 8.4 and 15.25 GHz frequencies, even for the maximum data rate of 200 Mb/s. While also feasible at 21.2 GHz, some sacrifice in operability is necessary and a much larger antenna is necessary.

More detailed descriptions of the individual subsystems are found in Section 5.0 for spacecraft equipments and Section 6.0 for the ground station hardware. The descriptions are in the form of technical parameters and cost estimates.

*See Appendix A

4.2 Local User Terminal (LUT)

Analysis and rationale for providing a configuration for the Local User Terminal (or Mode II Terminal) is summarized in this Section. Supporting technology and analysis is found in the appendices.

4.2.1 Guidelines and Assumptions

The requirements and needs for a local user are less well defined than for the Regional Center. Therefore, a less specific system configuration is to be expected as a result of any analysis. The general requirements envisioned can be stated rather simply. Briefly, this system is to satisfy a real time need for data (such as pollution detection), a broadcast mode is desirable, and spacecraft prime power available is nominally 40 watts. Beyond these very general guidelines supplied by NASA, a wide range of requirements on resolution, spectral band, repeat period, etc., are encountered. As a consequence, the effort during this study has been to describe the system parametrically thus enabling the cost and complexity to the user to be a factor in the ultimate configuration.

Two assumptions or clarifications on the above guidelines are reasonable. First, it is assumed that the broadcast mode implies utilization of an omnidirectional antenna on the satellite such that multiple users may be simultaneously serviced. A second factor, which is related, concerns the area of interest of the local user. It is assumed in this analysis that the need for "real time" data is restricted to a radius of 500 miles from the user. This parameter can be used to determine the ground elevation angle limits, satellite look angle, and typical pass durations as discussed in Section 4.2.3.1.

Both analog and digital transmission are considered. Both techniques have advantages which are discussed in the analysis of this section and in Appendix A.

4.2.2 System Alternatives

There is potentially a wide range of possibilities for the Local User Terminal (LUT) and associated satellite equipment. However, the range of considerations can be somewhat limited by recognizing that the link is frequency independent to an extent. If the problem is approached on the basis of a constant gain antenna on the satellite and a constant aperture on the ground, the only frequency dependent link variables are atmospheric losses, receiving system noise temperature, and miscellaneous hardware constraints. Within this framework several system alternatives remain which have some unique features related to the frequency of operation. The general alternatives and their distinguishing features are summarized below.

For discussion purposes the alternatives are divided into three major categories: 1) low resolution system, 2) VHF/UHF system, and 3) S-Band system. The low resolution approach is characterized by being presently off-the-shelf. While alternatives (2) and (3) are similar conceptually, a system operating at 400-500 MHz or less could utilize a very cheap antenna and tracking system. This leads to identifying the VHF/UHF system separately. Major emphasis has been placed upon the S-Band system and the results are presented parametrically. While a higher frequency could be utilized, there is no advantage to doing so and a cost penalty would be incurred. Therefore operation at higher frequencies has not been considered as a likely or desirable alternative for the LUT system. A different system approach to satisfying needs of local users has been recognized but is beyond the scope of the present study effort. This approach would circumvent the need for special ground terminals. The user would receive via land based communication links the data of interest from the Regional Collection Center. There are a number of trade offs necessary to optimize such a facsimile distribution system and they should be the subject of further study. Most probably, requirements will dictate a necessity for the facsimile system and capability for direct spacecraft to user transmission. The two systems could then supplement each other.

Low Resolution System. A system can be configured for the present application which has characteristics similar to those of the APT Nimbus system. This would provide low resolution image data to the local users at very low cost. Nominal expectations would place the resolution achievable at about 2 Nm and the user cost around \$10,000. While this is a very attractive system for weather forecasting and monitoring purposes, it appears that the data quality and resolution achievable are not adequate for the ERTS/DRGS application. For this reason and because it is very well documented, [25] the low resolution approach per se is not considered further in this report.

VHF/UHF System. A system can be configured to operate in the 100-500 MHz frequency band and to achieve high quality image data for the local user. The distinctive feature of this approach is the relatively low antenna gain required. This allows utilization of a low cost antenna, facilitates the solution to the tracking problem, and therefore minimizes cost to the user. The primary problem appears to be that of frequency allocation. Approximately 1-5 MHz of RF bandwidth would be required and operation in a clear channel is desirable.

S-Band System. The so called S-Band System presents a configuration generally applicable to a range of frequencies from 500 MHz to 10 GHz. However, operation at S-Band within one octave of 2 GHz appears most probable. Such a configuration provides the local user a capability for medium to high resolution image data at costs below the target of \$500,000. Naturally the precise capability varies with system sensitivity (antenna size) and attendant cost. This system can be provided

a Data Collection System (DCS) capability with negligible impact on the inherent imaging system capability. A number of approaches are feasible for satisfying any DCS requirement and specification of the optimum method is outside the scope of this study. However, feasibility of the concept is demonstrated.

The majority of the analyses in Sections 4.2.3 and 4.2.4 is directed toward definition of the appropriate parameters of the S-Band System.

ERTS Facsimile System (EFS). EFS is recognized as a system approach which would replace/supplement the capability provided by LUT. Data limited only by the quality available at the RCC could be provided to local users via land based transmission subject to a number of system level trade-offs. Further study is required to provide any additional insight into the desirability and effectiveness of EFS.

4.2.3 Link Analysis for LUT

Definition and trade-off considerations for the LUT communications link are summarized by a discussion of four major topics. These are: 1) consideration of the satellite antenna approach, 2) computation of the link budgets, 3) consideration of relative merits of analog and digital transmission, and 4) the relationship of data rate to resolution capability. These topics are considered in the remainder of this section.

4.2.3.1 Spacecraft Antenna for LUT

There are a number of methods by which an antenna for the spacecraft could be configured. Due to the stated guidelines, consideration is restricted to a fixed shaped beam antenna or a set of electronically switchable antennas. In choosing the most desirable approach, overall system requirements and the trade-off between simultaneous gain and coverage must be considered.

It is desirable that any fixed antenna, considered for this application have a beam or pattern that is shaped such that it compensates for the variation in path length attenuation which changes with satellite look angle. This variation was calculated in Section 3.1 and is presented for convenience in Figure 4.2.3.1-1. One type fixed antenna that has the desired characteristics is a turnstile type of antenna such as that presently planned for the ERTS-A spacecraft. The pattern for this antenna has been drawn on Figure 4.2.3.1-1 for direct comparison with the path length attenuation variation. It can be seen that this antenna does compensate in a desirable manner for the path length attenuation variations. One could use this antenna and calculate link budgets for path length of 1600 nautical miles and use an antenna gain +5 dB.

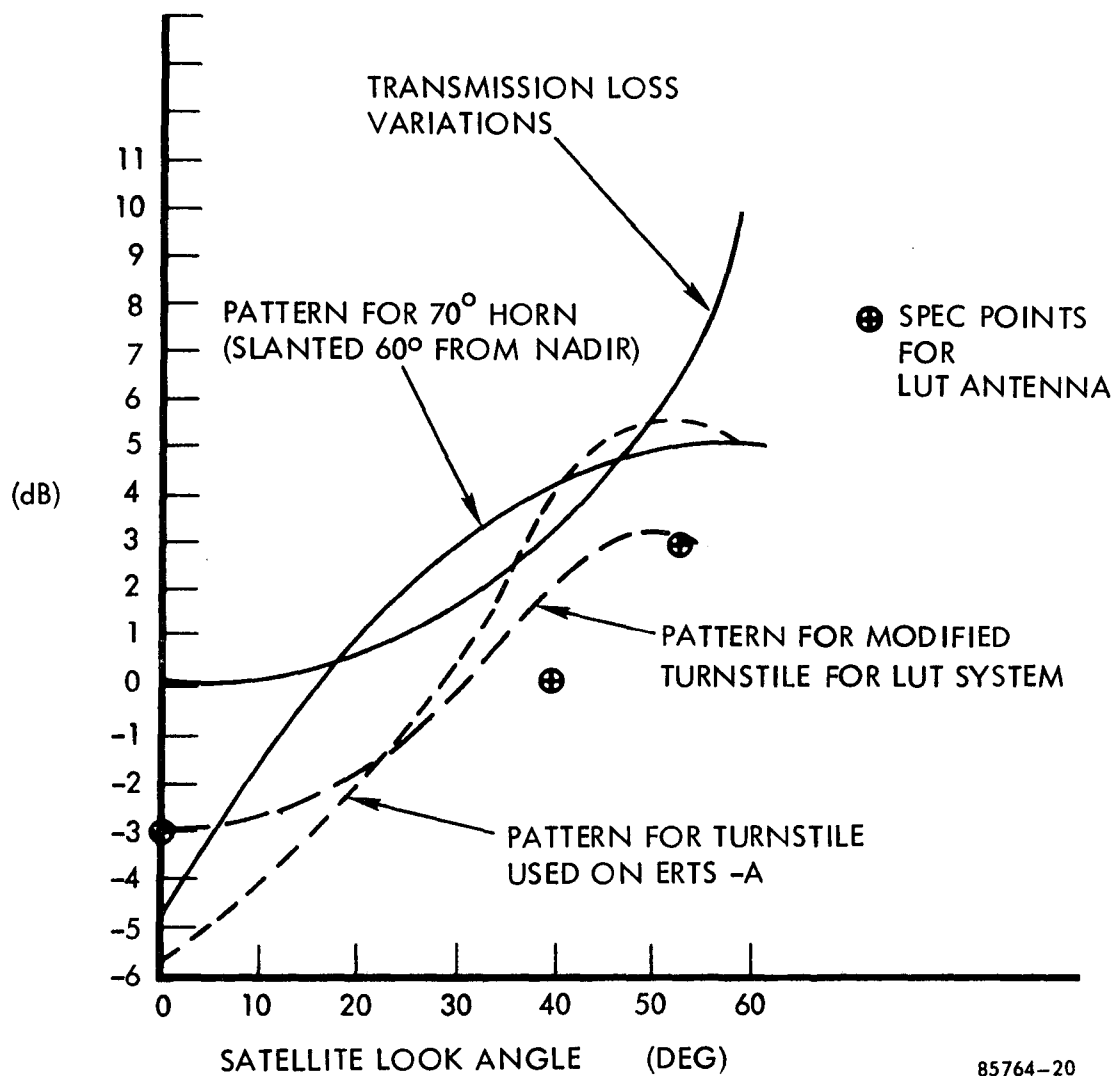


Figure 4.2.3.1-1. Spacecraft Antenna Gains

Another technique for achieving similar types of pattern coverage would be to use a phased-array antenna where the phasing of the various elements is fixed. It is likely that a closer pattern shape to the attenuation shape could be achieved. Both of these antennas have circular polarization which is desirable. Circular polarization of the spacecraft antenna eliminates the necessity of polarization tracking equipment in the ground antenna, which would be required for linear polarization to minimize polarization mismatch losses. However, axial ratios must be kept small to minimize polarization losses.

The ERTS-A antenna has been designed to operate with a ground station to 5° minimum elevation angle in order to maximize coverage. This extent of coverage is unnecessary for the present application and modifications in the antenna pattern can provide increased link gain. From the geometric analysis given in Section 3.1, it is seen that any pass for which the subtrack comes within 500 N miles of the terminal of interest has a peak elevation angle of approximately 40° or greater. It is also seen that for such a pass a 5 minute contact duration or greater is assured by a system which operates to a minimum elevation angle of 25° . The satellite look angle, measured from Nadir, which corresponds to a ground elevation angle of 25° is 52° . Therefore, a spacecraft antenna designed for adequate operation over a look angle of 52° (rather than 60° for ERTS-A) is satisfactory for the LUT application and is capable of improved performance.

From examination of the path loss curve, reasonable specification points are derived as presented in Table 4.2.3.1-1. A pattern which satisfies these specification points is also shown in Figure 4.2.3.1-1. This pattern could be achieved by modifications of the basic ERTS-A turnstile antenna.

Table 4.2.3.1-1. Specification Points for Mode II Spacecraft Antenna

Satellite Look Angle	Minimum Antenna Gain
0°	-3 dB
40°	0 dB
52°	3 dB

For the subsequent link analysis, an antenna gain of 3 dB is utilized at the slant range of 950 N miles which corresponds to a 52° look angle on the satellite. Obviously, a perturbation in desired user coverage area would perturb the link accordingly if antenna modifications were performed. However, further modification from the ERTS-A antenna does not appear particularly attractive. Reduction of coverage to the stated limits has moved the operating point away from the high slope extreme of the path loss variation plot and further variations do not produce significant variations in link gain available.

An additional antenna type considered in the study was electronically switchable beams. This category of antenna could be composed of any number of beams with orientations such that any visible ground station could be serviced by one beam, and that would be chosen by electronic switching. One simple example of this type is four horn antennas with each antenna pointing into a different quadrant of the spacecraft look angle geometry. The pattern for a four horn arrangement has been drawn on Figure 4.3.2.1-1 and illustrates what can be achieved with this technique. As can be seen from the pattern, the gain is several dB higher than the single turnstile over most of the angular coverage required. However, the deficit gain of this antenna, i.e., at the end-points, is almost identical to the turnstile and therefore provides no increase in effective radiated power. It has the disadvantage that only one quadrant could be serviced at given instant. Although various other combinations could be configured, this does not seem to be a desirable approach to the spacecraft antenna problem.

4.2.3.2 Link Budgets

Link budgets for the S-Band and VHF/UHF system configurations are computed here. These two cases are treated separately, in spite of the frequency independent characteristics of the link, due to different assumptions and constraints which are made obvious in the analysis. The S-Band system is given in Table 4.2.3.2-1. As previously noted the computations are valid over a wide frequency range (nominally 2 octaves minimum). A transmitter power output of 10 watts is easily achieved at S-Band from the 40 watts available. Present technology would dictate a TWT, but such capability from space qualified solid state elements is expected in the 1973-75 time frame. The antenna gain and space loss figures correspond to the previous section and Figure 4.2.3.1-1. While the space loss is computed for 2.2 GHz, other frequencies could be utilized and result in the same required ground antenna size. For the ground receiving system, a solid state preamplifier provides excellent reliability and reasonably low noise figure, coupled with low cost. A conservative value of 5 dB noise figure for the preamplifier/downconverter is utilized. Allowing for a 2 dB line loss the system noise temperature referred to the antenna is

$$\begin{aligned}
T_s &= T_{\text{ant}} + (L - 1) T_{\text{line}} + LT_{\text{preamp}} \\
&= 80^\circ + 170^\circ + 1000^\circ \\
&= 1270^\circ \text{K}
\end{aligned}$$

The corresponding noise power density is -167.3 dBm/Hz.

Table 4.2.3.2-1. Budget for S-Band System

Power transmitted	40 dBm
Antenna gain	3 dB
Line loss	<u>1 dB</u>
ERP	42 dBm
Space loss	164.0 dB
Atmospheric Loss	0.2 dB
Tracking Loss	<u>1.0 dB</u>
Power Available	-123.2 dBm
Noise power density	<u>-167.3 dBm/Hz</u>
Carrier to noise density	44.1 dB/Hz
Margin	<u>6 dB</u>
Available C/KT (0 dB antenna)	38.1 dB-Hz

The objective for the LUT Configuration is to provide a parametric description. It appears that an antenna size for the S-Band system in the 2-10 foot diameter best meets the cost performance trade-off imposed. The carrier to noise ratio (C/KT) for antenna sizes in the 1-20 foot range is plotted in Figure 4.2.3.2-1. This computation is simply the sum of 38.1 dB-Hz and the appropriate antenna gain assuming 55% efficiency.

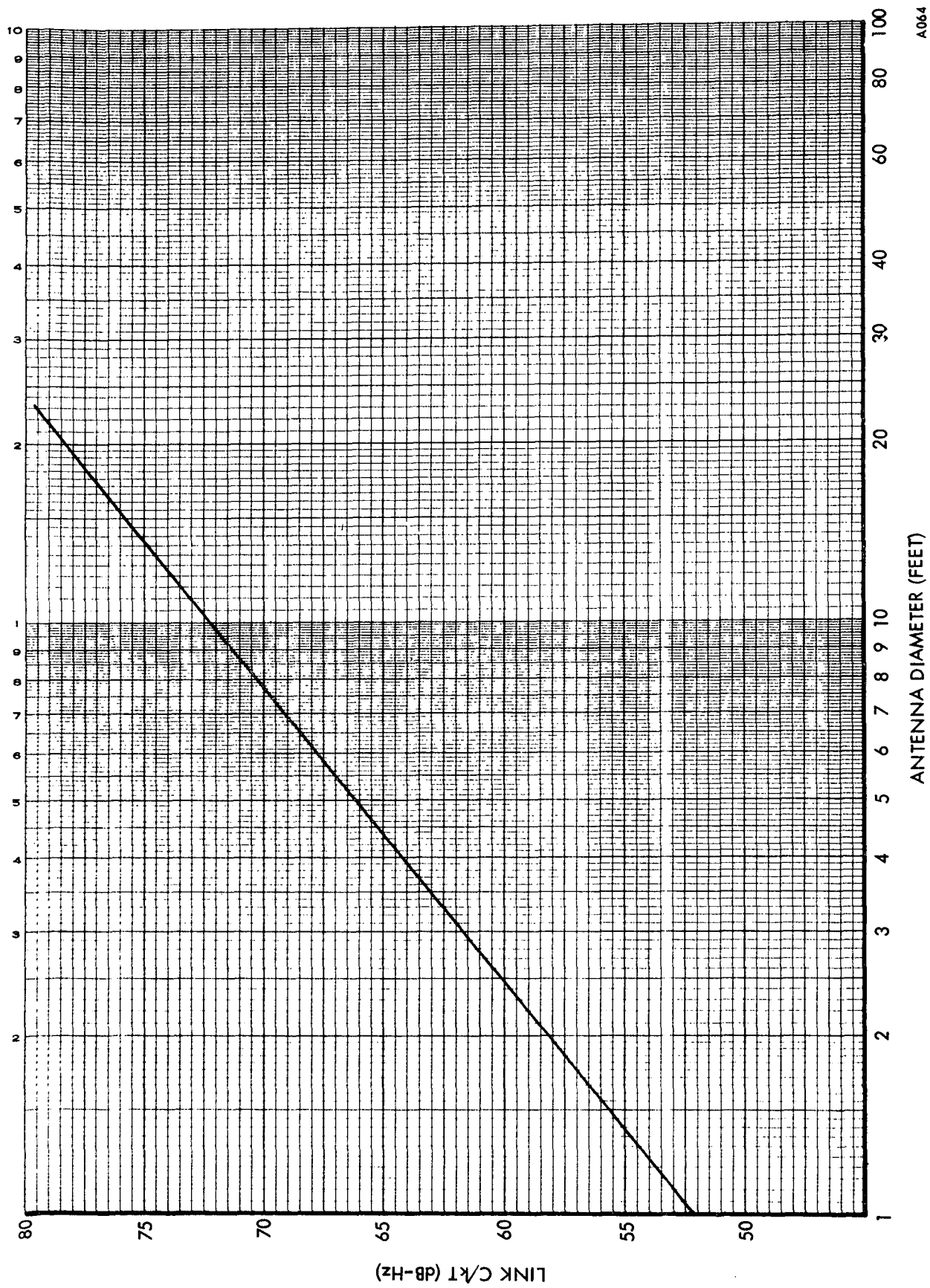


Figure 4.2.3.2-1. S-Band System Link Capacity

A064

Analysis for the VHF/UHF system is presented with a constant gain rather than constant aperture antenna on the ground. A gain of 18 dB is achievable at nominal cost at frequencies below 500 MHz and such an antenna makes manual tracking feasible thus reducing user cost considerably. With this assumption the link capacity as a function of the carrier frequency as computed in Table 4.2.3.2-2. As noted, the nominal value of 6 dB margin is included in the computations and other parameter values are selected for comparison ease to the S-Band system. The -167.3 dBm/Hz kT is achievable at VHF with a 300°K antenna temperature and 6.7 dB noise figure. The resultant link capacity (dB-Hz) is plotted versus frequency in Figure 4.2.3.2-2.

Table 4.2.3.2-2. VHF/UHF System Link Budget

Power Transmitted	40 dBm
Antenna gain	3 dB
Line loss	<u>1 dB</u>
ERP	42 dBm
Space loss (950 Nm)	$97.3 + 20 \log f^*$
Atmospheric and Tracking loss	1.2 dB
Antenna Gain	<u>18 dB</u>
Received Carrier Power	$-38.5 - 20 \log f^*$
Noise Power Density	-167.3 dBm/Hz
Margin	<u>6 dB</u>
Available C/KT	$122.8 - 20 \log f^*$

*f in MHz

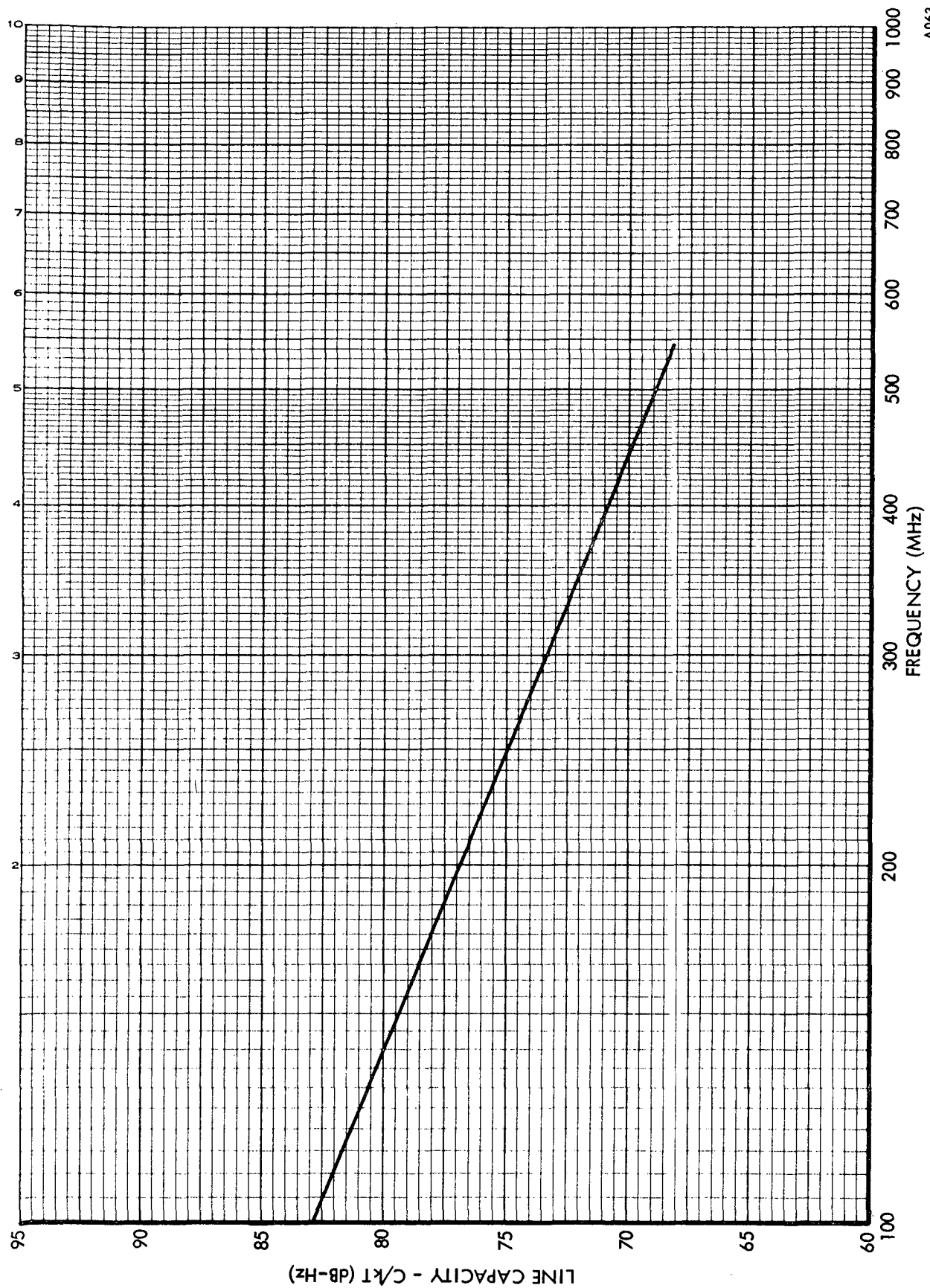


Figure 4.2.3.2-2. VHF/UHF System Link Capacity

A063

4.2.3.3 Analog vs. Digital Transmission for LUT

A modulation technique for the local user application is dependent upon many factors. From a performance and complexity to the user viewpoint, analog FM is the favored approach. A performance comparison is provided in Figure 4.1.2.5.1-1 where it is seen that a video signal to noise ratio of 30 dB using FM can be achieved with approximately 3 dB less gain than for PCM/PSK. Several aspects of analog and digital transmissions are explained in Appendix A. Figure 4.2.3.3-1, abstracted from that appendix, illustrates the relative spacecraft and ground complexities for a number of modulation techniques. Analog FM yields a minimum complexity demodulator while digital PSK minimizes the modulator complexity.

It is to be expected that a final selection of modulation technique will be greatly influenced by design considerations for the satellite and the manner in which the transmission system for the Local User Terminals interfaces with the sensors and primary multiplexing system. This aspect of the problem is considered further in Section 5.0. Since a clear cut choice is not evident, performance is predicted for both methods in subsequent analysis.

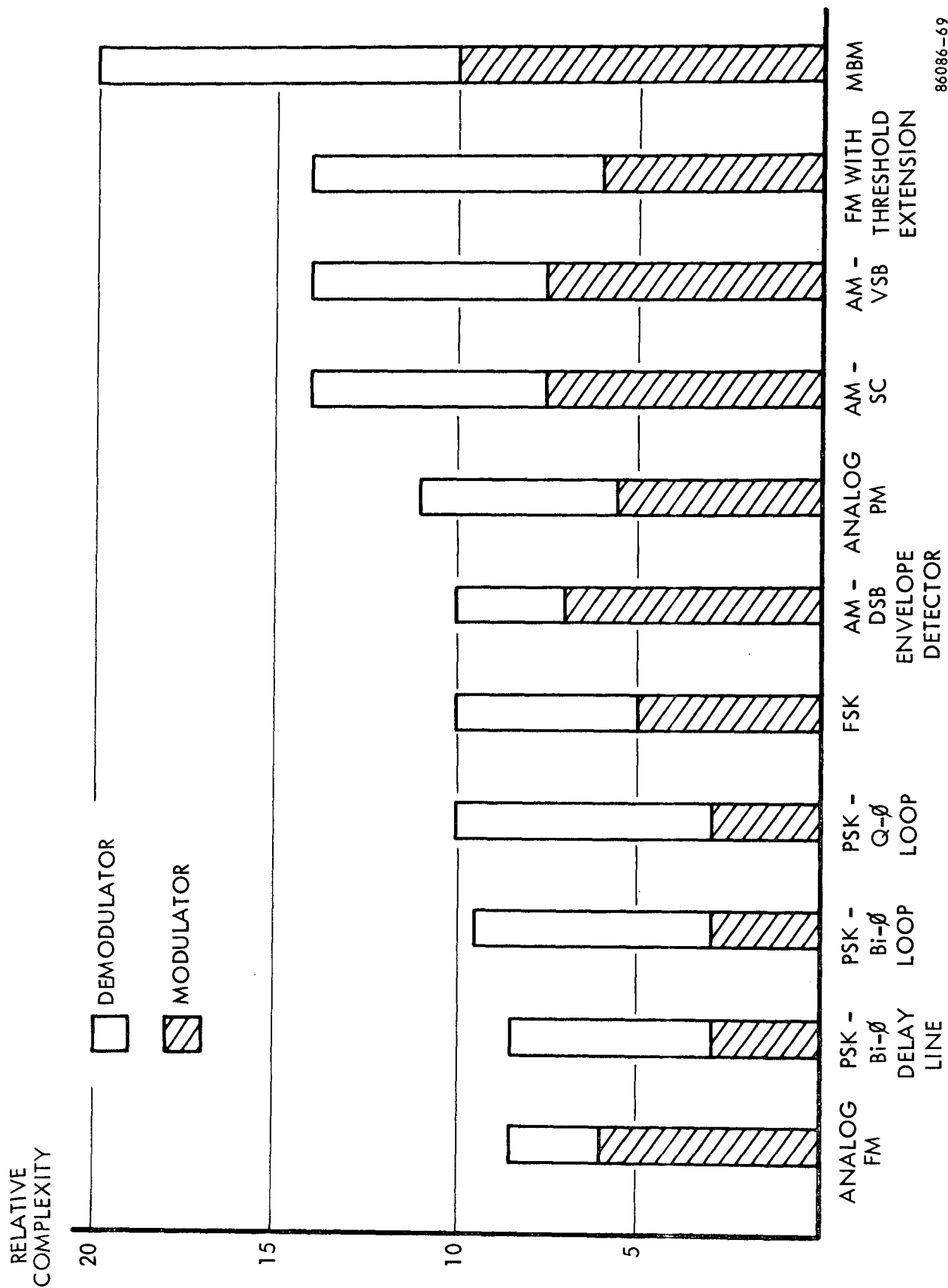
4.2.3.4 Resolution versus Data Rate

The approach utilized in this study effort is somewhat unique and leads to a requirement to have the capability for inferring ground resolution from link capacity, or data rate. This capability allows results to be presented in a meaningful form to potential users who may understand resolution but not appreciate nor have an interest in communication theory. Link capacity has been computed and solution of the resolution problem will allow a parametric presentation of the candidate system approaches. This is done in Section 4.2.3.5.

A derivation showing the functional dependence of resolution to data rate is given in Appendix A. Such a derivation requires a number of assumptions to be made and therefore produces a result which is subject to variation. Nevertheless, in the present situation reasonable parameter values may be assumed and an indicative result obtained. Figure 4.2.3.4-1 presents a graph giving resolution as a function of bit rate. Image width is a parameter. The primary assumptions in computation of the data for this figure are ERTS-A orbit, 4 bits per sample, and Kell factor of $\sqrt{2}$.

Digital transmission is implicitly assumed. It is also desirable to relate resolution to data rate (i.e., bandwidth) for analog transmission systems. The appropriate conversion factor is 8 in this case.* Therefore, a 100 kHz analog bandwidth in the

*Equivalent analog bandwidth is a subject for debate and general agreement on a suitable conversion factor is probably not attainable. For this analysis it is assumed that the bit rate is equal to twice the analog bandwidth times the number of bits per sample.



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Figure 4.2.3.3-1. Comparison Between PCM Bi-Phase and Analog FM Systems

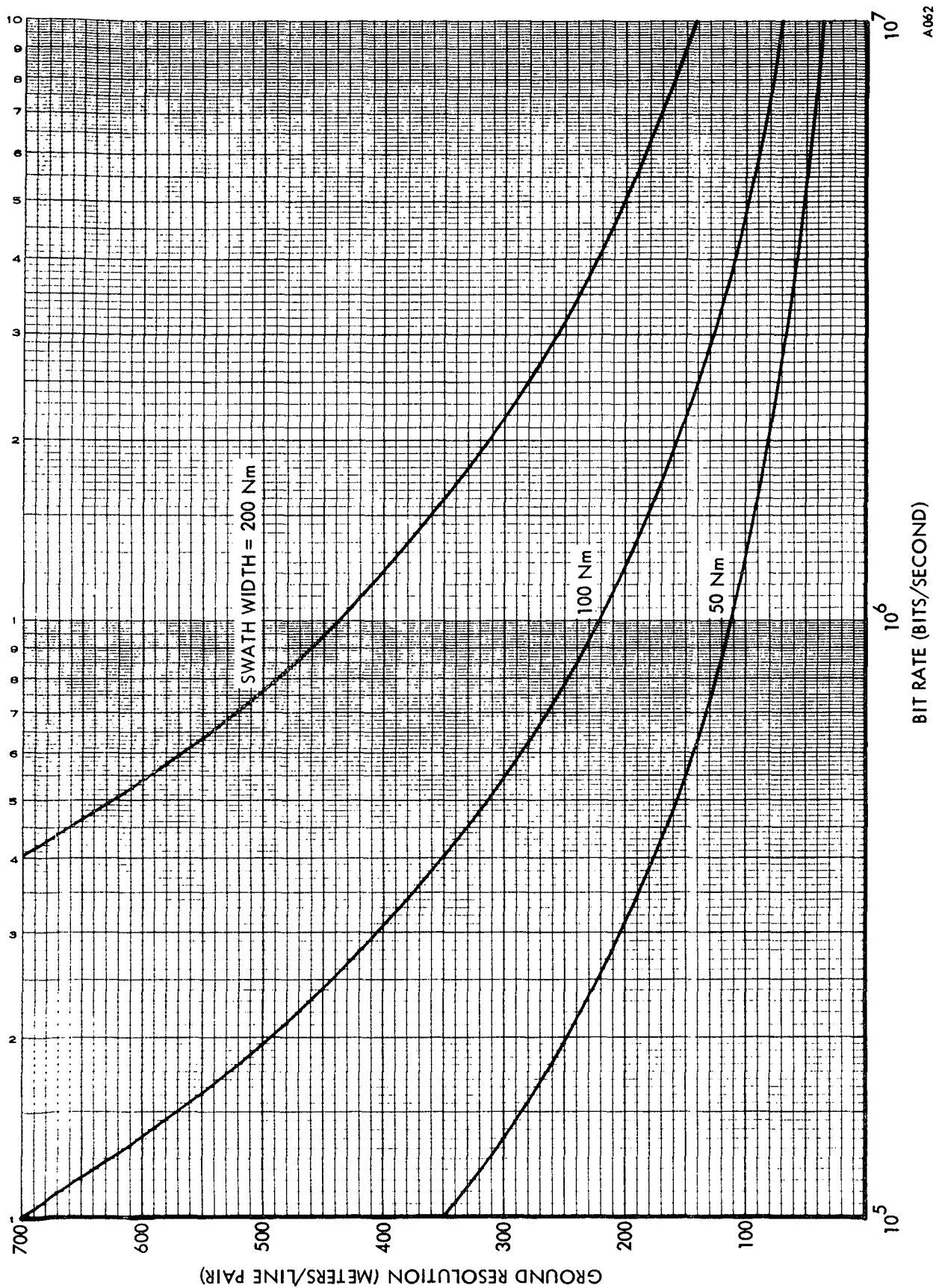


Figure 4.2.3.4-1. Ground Resolution as a Function of Data Rate for ERTS Parameters

baseband produces an inherent resolution of approximately 250 meters/line pair for a 100 Nm image width, while 250 kHz corresponds to approximately 160 meters/line pair.

4.2.3.5 Parametric Link Capability

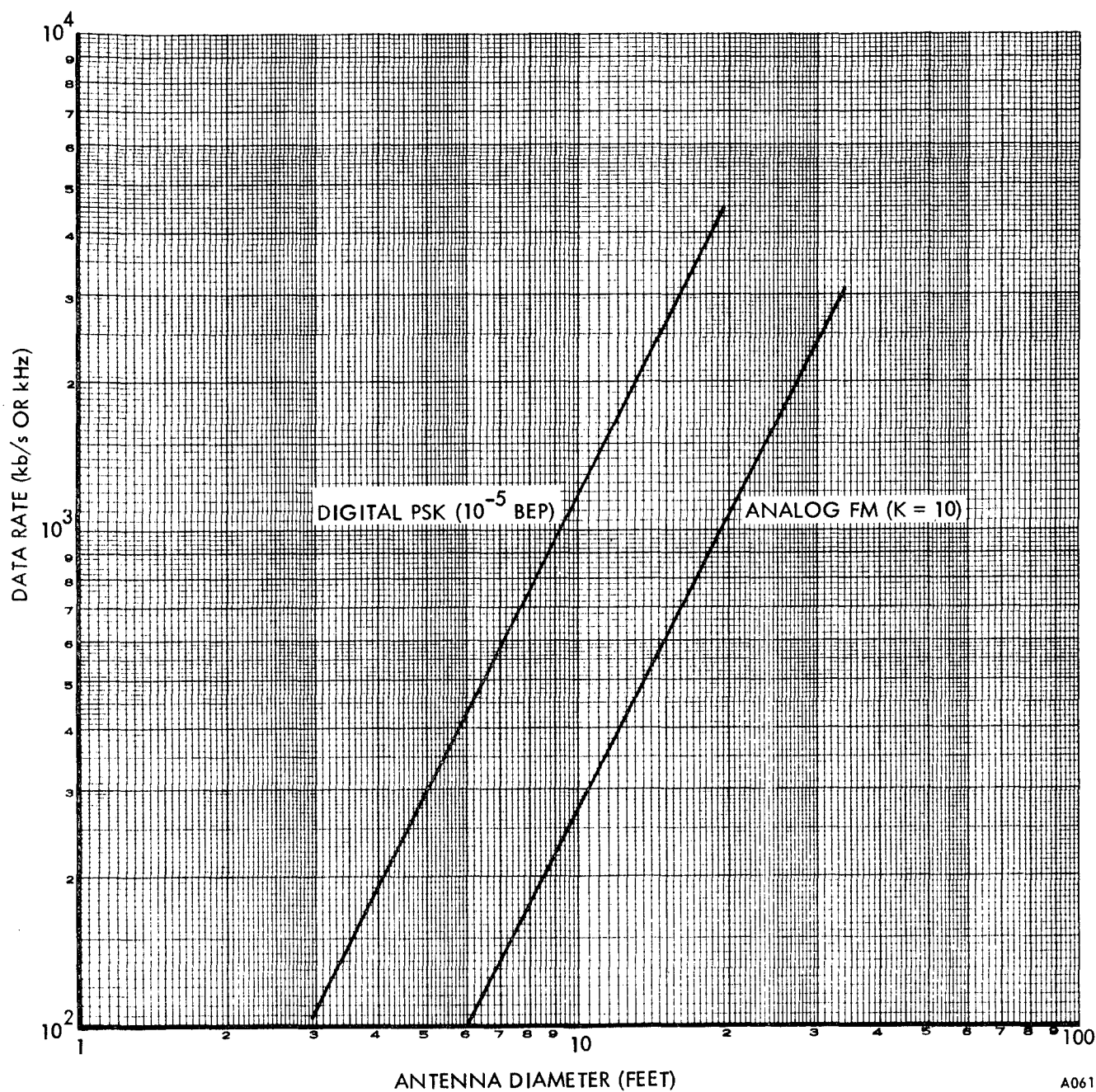
From the analyses performed previously in this section, link capability in terms of bit rate for digital systems or video bandwidth for analog systems can be determined as a function of the independent variables for the alternate approaches (frequency for the VHF/UHF system and antenna diameter for the S-Band System). These functional dependencies are given in Figures 4.2.3.5-1 and 4.2.3.5-2 for the S-Band and VHF/UHF alternatives respectively. These figures along with the relationship of resolution to data rate provide the desired results.

An interesting comparison is possible and provides additional insight into the relative advantages and disadvantages of the two alternative configurations. At a frequency of 335 MHz, the VHF/UHF System provides link capacity equivalent to that of the S-Band System with a 10 foot diameter antenna. These capacities with the corresponding resolutions achieved for 100 Nm swath width are provided in Table 4.2.3.5-1. Note that at lower carrier frequencies the VHF/UHF system will outperform the S-Band System while decreased performance is obtained at higher carrier frequencies. With this factor and the decreased complexity of the VHF System it should receive strong consideration for the local user systems.

Table 4.2.3.5-1. VHF/UHF System at 335 MHz and S-Band System with 10' Antenna

	Data Rate	Resolution
Analog	270 kHz	150 m/line pair
Digital	1.18 Mb/s	205 m/line pair

An additional factor worth emphasizing is the relative performance provided by analog and digital transmission. The analog system provides greater resolution than the corresponding digital system and at an increased equivalent signal-to-noise ratio (30 dB versus 24 dB). This along with reduced complexity/cost for the user makes analog FM the favored approach for the given application.



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Figure 4.2.3.5-1. Video Bandwidth/Bit Rate for S-Band System

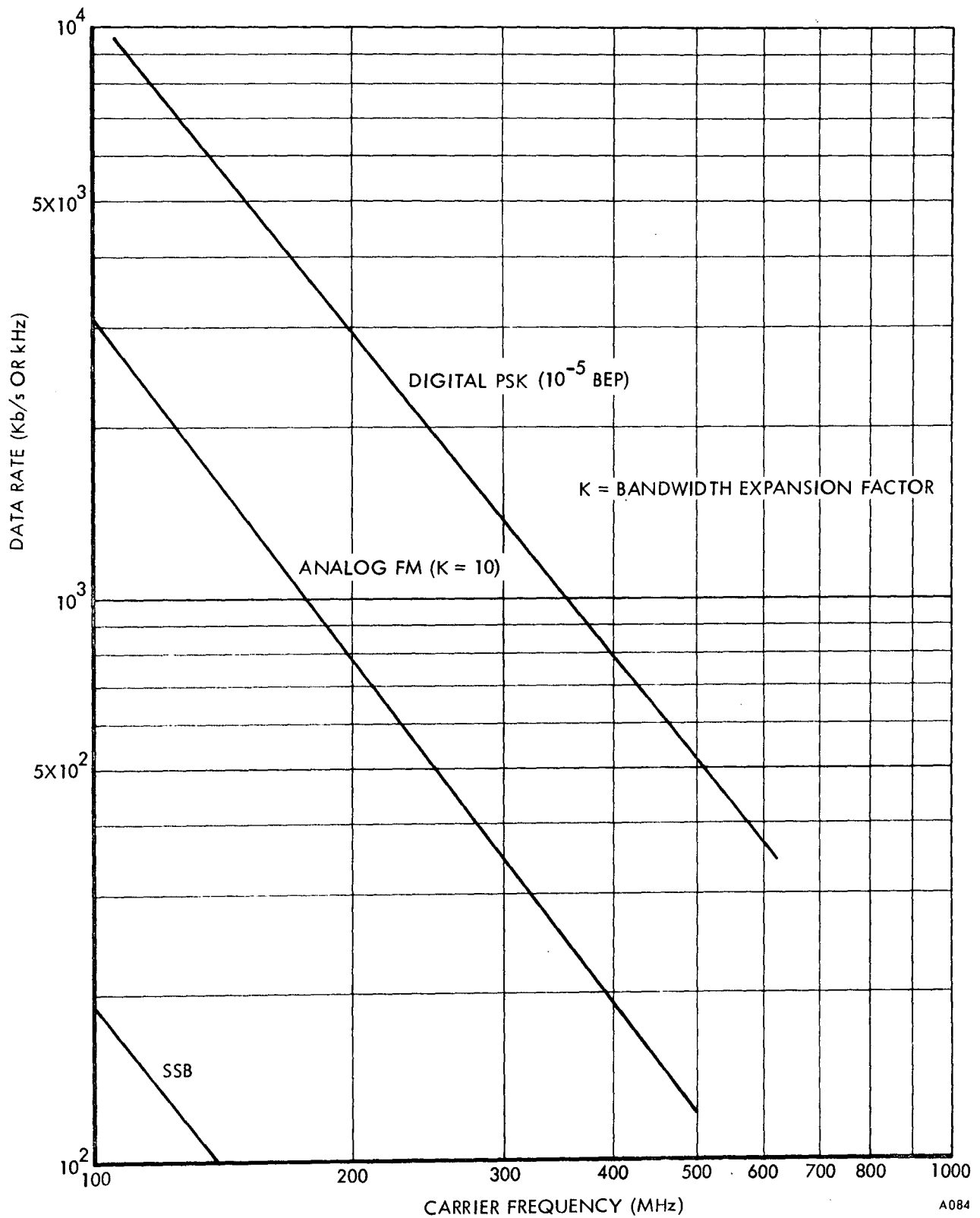


Figure 4.2.3.5-2. Video Bandwidth/Bit Rate for VHF/UHF System

4.2.4 Channel Coding Considerations for LUT

Channel coding implies that redundancy is added to the transmitted data in a manner which allows bit errors to be detected and corrected at the receiver processor. The principal reason for coding is to make more efficient use of the communication channel that is available. The process of adding redundant bits to a digital transmission can be implemented in three basically different manners depending on the system configuration, transmission rate, and type of data being transmitted. These three schemes are (1) error detect and delete, (2) error detect and retransmit, and (3) forward error control.

Error detect and delete schemes are useful in applications where the data is relatively redundant and the cost of discarding a few bits of data is not high. Multi-spectral scanner data is singularly unique which precludes the use of this scheme.

Error detect and retransmit schemes require input data to be buffered until reception of a verification that the message is correct. The data rate of the Mode II system would require a buffer of an impractical length which necessitates rejection of this scheme.

Forward error control or error correction coding utilizes the transmission of highly redundant data so that transmission error can be corrected in addition to being detected. The two available types of codes are block codes and convolutional codes. As the name implies, the block coding schemes take a block of M data bits and add $N-M$ redundancy, or parity, bits. Partial specification of a particular code using these definitions is (N,M) . Note that the band spread factor is N/M . Convolutional codes add redundancy by continuously operating on the input bit stream to produce a new, higher rate, bit stream with desirable characteristics (i.e., error correcting capability). The performance gain of the convolution coding schemes is affected by the bandspread factor as well as another parameter, the constraint length K . This constraint length indicates the length of time, measured in number of bits, that a particular data bit will be held in the coding circuitry to directly affect the new bit stream. Increasing K will raise the performance gain at the expense of more complexity.

Convolutional codes are more powerful than block codes in the sense that for a given level of complexity, a larger dB gain is available. They also tend to result in simpler encoder implementation due to the fact that synchronization information is not required at the decoder (it can be extracted from the encoded message) and there is a minimal amount of rate buffering at the transmitting end. Practical implementation schemes for decoding convolutional codes do not exist above 10 to 20 Mb/s but this has no impact on the Mode II system which will operate with an information rate about 1 Mb/s if digital transmission is selected.

In contrast to convolutional codes, block codes require that additional information be inserted at the transmitter so as to determine block synchronization. Block decoder implementations can operate at rates as high as 150 Mb/s. The one significant advantage of block codes in the present considerations is that bandspreading can be kept as low as 6/5 with several dB gain up to a 5 Mb/s rate.

There are various schemes for decoding convolutional codes; such as the maximum likelihood decoder, the approximate a posteriori probability threshold decoder, and the Fano decoder. In general, convolutional codes are used with a band-spread factor of two or more.

A comparison of these various forms of coding is given in Table 4.2.4-1. It can be seen that the Fano and maximum likelihood algorithms give very nearly the same performance for similar complexity. In the future the relative value of these two will depend on cost and speed of large buffers (Fano) versus large scale production and integration of the electronics needed for the maximum likelihood decoder.

For lower rates, (≤ 2 Mb/s) and only 2 - 3 dB gain, the AAPP threshold decoder is the least complex.

The coding gain can be utilized in various ways; to decrease antenna size, decrease spacecraft RF output, increase allowable data rate, or some combination of these. Potential effects of coding gain on the S-band system are shown in Table 4.2.4-2. Similar parameter variations can be achieved with the VHF/UHF system but the allocation/spectral occupancy makes channel coding less attractive there.

Thus, the utilization of moderate complexity channel encoding with 3 dB gain allows an increased digital information rate if other parameters remain fixed. The 2.36 Mb/s information rate corresponds to a resolution of approximately 145 m/line pair compared to 205 m/line pair without coding. The capability of the digital system with coding is essentially equivalent to that of the analog system and coding appears to be desirable if digital transmission is used.

4.2.5 DCS Data

The present ERTS (A&B) Data Collection System contains three distinct equipments; the data collection platforms, spacecraft receiver - frequency translator, and receiving site equipment (RSE). The platforms can be located anywhere on the Earth's surface (provided there is suitable environmental protection) to sample sensor outputs, convert, format and encode data messages for transmittal to the orbiting ERTS satellite. The platforms transmit pseudo randomly (about every 90 or 180 seconds) to produce an acceptable probability of successful satellite receptions. The ERTS satellite

Table 4.2.4-1. Summary of Current Channel Coding Hardware and Performance

Decoder	Rate	Coding Gain (dB) $P(E) = 10^{-5}$	Complexity (IC Packages)	Bandspreading Factor
Maximum Likelihood	200 Kb/s	4.5 - 5	250	2
	1 Mb/s	4.5 - 5	550	2
	9 Mb/s	4.5 - 5	1900	2
Fano *	1 Mb/s	4.5	700	2
	8 Mb/s	4 - 4.5	1200	2
AAPP	2 Mb/s	2 - 3	40 - 90	2
Block ** Codes	1 Mb/s	3.3	300	6/5, 5/3, 3/2
	5 Mb/s	2 - 3	200 - 300	6/5, 5/3, 3/2

* Memory is converted to equivalent IC packages.

** Includes group sync logic and buffering.

Table 4.2.4-2. Possible Effects of Coding Gain on S-Band System

Coding Gain	0 dB	3 dB	5 dB
Antenna Diameter	10'	7'	5.6'
S/C RF Power Out	10 W	5 W	3.2 W
Information Rate	1.18 Mb/s	2.36 Mb/s	3.72 Mb/s

receives the platform messages, translates the UHF signal to a 1024 KHz subcarrier, and modulates an S-band transmitter for downlink communication. The RSE demodulates, synchronizes, and decodes the data message for immediate transmittal to users over land-lines or tape recording for later transmittal to users. The ERTS-DCS is intended to provide the user with near realtime data collected from various remote, distributed locations. The data will be used for detecting water and air pollution trends, monitoring agricultural conditions, measuring wind and water actions, and to identify precipitous conditions prior to natural disasters. The ERTS (A&B) DCS will provide data retrieval from data collection platforms located within the continental United States, and has significant capability for coverage of platforms located in the Pacific and Atlantic coastal areas and parts of Canada and Mexico. Additional ground terminals can allow expansion to worldwide coverage.

Operational earth resource observation systems can utilize a DCS with characteristics similar to those described above. The ERTS A satellite receiver/frequency translator will provide a subcarrier channel for downlink transmission with other onboard data. Frequency division multiplexing of the DCS signal and MSS data on the downlink provides a degree of independence and can be accomplished with insignificant degradation to the MSS link performance previously computed. It should be noted, however, that the transmitter power amplifier must either operate in a linear mode or the frequencies must be carefully selected in order to avoid intermodulation distortion.

Table 4.2.5-1 is a link budget to demonstrate the ease with which a DCS capability can be added to the Mode II terminal configuration. The budget assumes "transmitted power" of .5 W dedicated to DCS data which results in simple implementation of the ground antenna and RF front end; however, the transmitter RF output could be increased or decreased with no adverse effect on system operation and requiring only a compensatory change to the receiver antenna gain. Other losses in the budget were taken from the link analysis for the S-Band system contained in Section 4.2.3. The antenna gain of 24.7 dB is achievable with a solid dish of three feet diameter, operating at S-band; although the dish size will likely be larger as dictated by the gain requirements of the MSS data channel. The present ERTS-DCS is required to achieve a 10^{-5} bit error probability (or 10^{-3} message error rate for the 95-bit message). The modulation mode is FSK and, with the convolutional coding gain, the predetection SNR in the bit rate bandwidth must be 13 dB for the desired error probability. The budget also includes a 6 dB gain margin as a conservative engineering pad.

Table 4.2.5-1. DCS Link Budget

S/C Transmitted Power (.5 W)	27 dBm
Antenna Gain	3 dBm
Line Loss	<u>-1 dBm</u>
ERP	29 dBm
Space Loss	-164.0 dBm
Atmospheric Loss	-.2 dB
Tracking Lose	<u>-1.0 dB</u>
	-136.2 dBm
Noise Power Density (KT)	<u>-167.3 dBm/Hz</u>
C/KT	31.1 dB-Hz
Bandwidth Factor (5 Kb/s)	-37 dB
Receiver Antenna Gain	24.7 dB
Gain Margin	<u>-6 dB</u>
Signal-to-Noise	13 dB

Power sharing as indicated of .5 watts for DCS data and the remainder of 9.5 watts for MSS data reduces the MSS link ERP by .23 dB. This results in a very slight perturbation to previous computations for the MSS link which were based upon 10 watts of transmitter power. However, the variation is small enough such that previous conclusions regarding data rate and resolution achievable are valid. The general conclusion is that DCS capability can be added for the local user link (and regional center link) with very little impact on the primary data channel.

The ERTS-DCS receiving site equipment utilizes highly selective receivers and complex maximum likelihood decoders. The RSE perform all of the demodulation and decoding functions allowing the spaceborne hardware to consist of a simple receiver-frequency translator. This is a sound practice when the system employs a few large terminals but the argument is reversed for a system with many, low cost Mode II terminals requiring DCS type data. Accordingly, although the Mode II system can provide DCS capability and operate well with the existing system configuration, there should be a further evaluation. The investigation should consider the cost and technical feasibility of optional system configurations with varying degrees of spacecraft complexity resulting in lower cost terminals including DCS capability.

5.0 SPACECRAFT CONFIGURATION

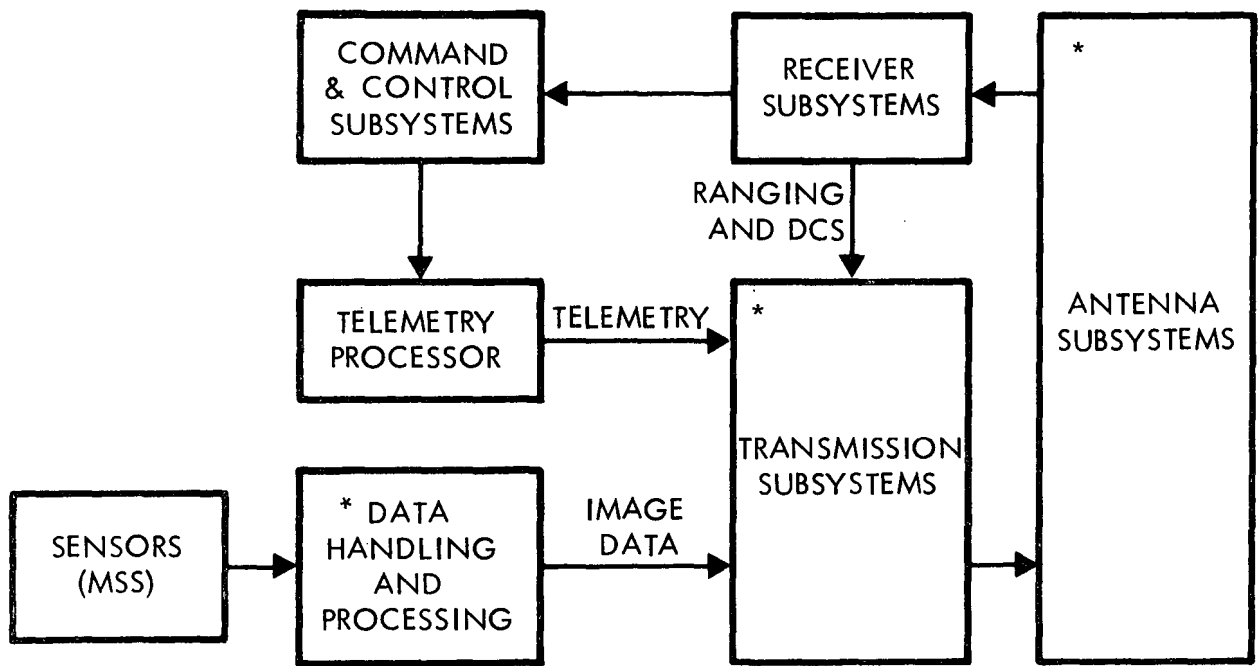
In the previous discussion and analysis a number of satellite parameters have been given, both implicitly and explicitly. In this section an overall description of the spacecraft configuration as it relates to this study effort is given. A number of alternatives are identified by satisfying user needs. Basic considerations are restricted to the communication systems as stabilization, thermal control, etc. are beyond the scope of this study.

5.1 General Description

The spacecraft will be configured to serve the needs of two distinct user types: 1) a Regional Collection Center which receives all data generated, and 2) a Local User Terminal which receives selected data at reduced rates. The respective systems will be referred to as Mode I for the former and Mode II for the latter. The Earth Observation Satellite (EOS) will be launched in the 1975 era and will represent an evolution from ERTS A & B. Experience gained from ERTS and the benefits accrued from analysis of the data will determine to a large extent the EOS payload.

Figure 5.1-1 illustrates the major satellite subsystems; those of primary interest to this study are indicated with an asterisk. The primary effort of this study has addressed the transmission and related subsystems of data handling and antenna. The receiver subsystem related to DCS has received some attention.

The EOS spacecraft, as with the typical unmanned spacecraft, will contain subsystems for command, data handling, thermal control, stabilization, communications, power and experiments. These are the power consuming equipments, and, additionally, there are passive mechanical subsystems such as the spacecraft structure and antennas. The electrical subsystems must be rigorously analyzed to determine their power requirements in order to size the power subsystem (solar arrays and batteries, radio-isotope power supplies, voltage regulators and voltage converters). It may be determined that the system design and available flight-qualified power subsystems do not have the power generation capability to support the data rates, or RF output levels, or simultaneous operation of experiments. Table 5.1-1 lists average power requirements of projected for EOS. The basis for these projections is an assumed similarity to ERTS and requirements which have been determined for the multiplexing and Modes I and II transmitters. Requirements are given for concurrent operation of a Return Beam Vidicon (RBV) and Multi-spectral Scanner (MSS). It should be noted that the RBV requires an inordinate percentage of this power and that the MSS alone presents a power drain of around 50 watts. This is another factor which favors the MSS as the primary sensor.



*PRIMARY STUDY INTEREST

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Figure 5.1-1. Major Spacecraft Subsystems

Table 5.1-1. EOS Power Requirements

Subsystem	Average Power (Watts)
Command	18
Thermal	25
PCM Data Handling (Using high speed, low power logic like CFL)	35
Transmitter - Mode I	40
Transmitter - Mode II	40
Attitude Control	75
RBV and MSS (Concurrent operation)	195

The one significant point to be made concerning Table 5.1-1 is that the power requirement of the PCM Data Handling subsystem is relatively high in comparison to the usual consumption of data handling subsystems. The change is due to the high power requirement of logic elements operating at speeds necessitated by the near 200 MB/S data rate. In fact, the 35-watt figure could be easily doubled or tripled by using other widely-accepted logic gates. Table 5.1-2 shows the speed-power performance of the popular Motorola Emitter Coupled Logic (MECL) and an innovation introduced by Radiation Systems Division called Current Feedback Logic (CFL). The propagation delays and power consumptions are based on the logic elements implemented in a Type D, master-slave flip-flop. Use of CFL was assumed in the 35 w power requirement of the PCM Data Handling subsystem.

Table 5.1-2. Flip-Flop Speed-Power Performance

Logic Element	Propagation Delay (nanoseconds)	Power (mw)
MECL III	1.8	210
MECL 10,000	3.0	110
"MECL IV" (estimate)	2.5	15 + 4/input

Table 5.1-2. Flip-Flop Speed-Power Performance (Continued)

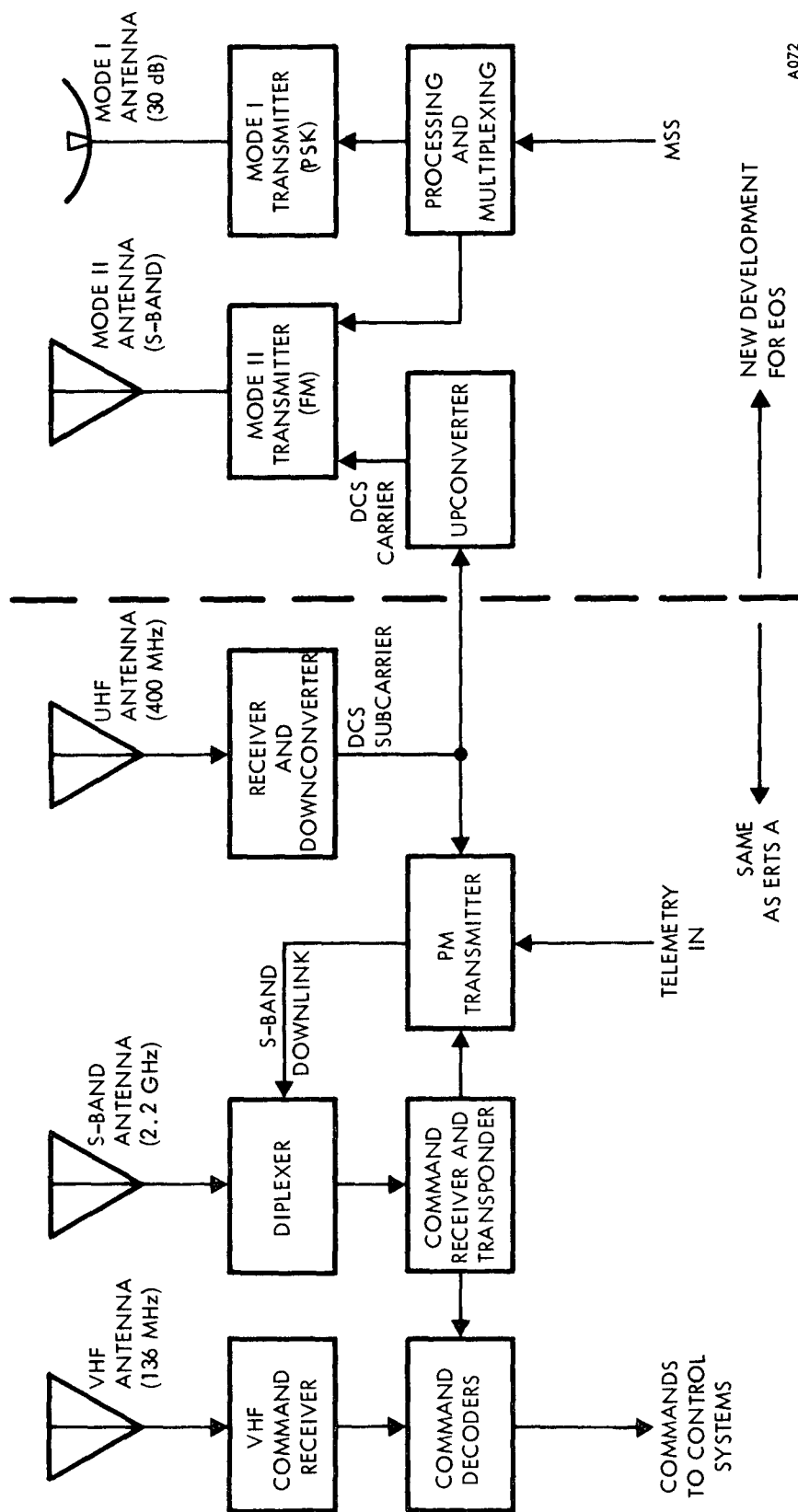
Logic Element	Propagation Delay (nanoseconds)	Power (mw)
CLF Discrete	2.5	10
CFL IC (estimate)	2.5	10

Figure 5.1-2 is a functional block diagram of one alternative for the EOS Communication Systems. There are six subsystems for space-ground communications indicated. The functional users of these subsystems will be command, tracking, via USB, telemetry, DCS reporting, Mode I and Mode II downlink communication. A redundant command system which allows command reception on either VHF or S-Band provides reliability and is compatible with the existing command and tracking network. Tracking is accomplished by the proven USB system with a coherent S-Band transponder. Telemetry and DCS data can also be placed upon subcarriers on the S-Band downlink. The spacecraft hardware for these three elements (command, tracking, and telemetry) can be identical to that utilized on ERTS. Further, such subsystems as thermal control, telemetry processor, etc. can be the same as proven on ERTS and NIMBUS before that. The remaining system elements are considered individually below.

5.2 Data Collection System

For the present system configuration, a DCS with a simple satellite receiver and frequency conversion unit is assumed. As discussed in Section 4.2, future investigations should consider placement of additional complexity on the satellite in order to reduce cost to the users.

For an antenna and receiver/down converter, the equipment to be utilized on ERTS A is suitable. This outputs a 1.024 MHz signal which can be used as a subcarrier on the S-Band downlink. This is done on ERTS A & B. Also, this same signal can be transmitted as a separate carrier (after appropriate frequency translation) on the Mode II transmitter. Such transmission would be programmed from the ground. This allows local users to receive and utilize DCS data with minimum development necessary. In fact, the user interested in DCS data only could use an antenna with an aperture as small as three feet in the configuration described. However, relatively expensive receiving site equipment is necessary in this configuration and alternatives should be considered.



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Figure 5.1-2. EOS Communication Subsystem

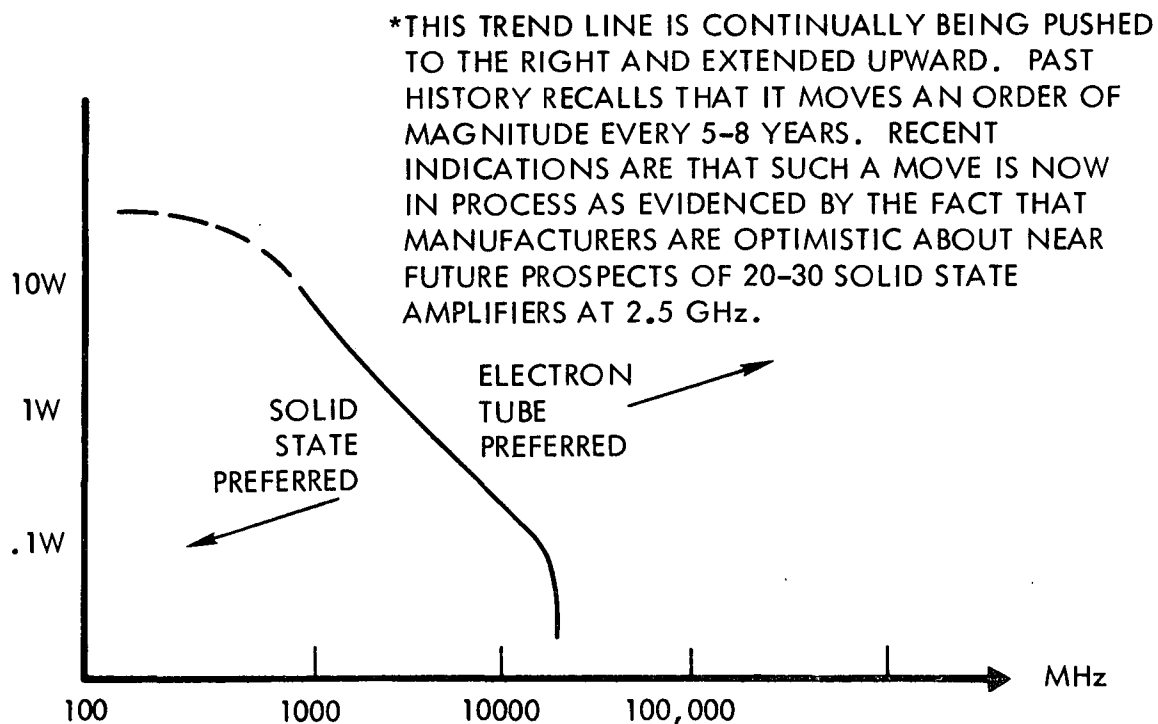
It is interesting to note that DCS capability can be provided on ERTS A & B to a user with an antenna as small as 6 feet in diameter. This would allow a user interested in DCS data only a relatively inexpensive system to achieve the desired capability. Further, with appropriate planning this study effort shows that such a terminal could also serve adequately as a LUT for an operational system. As a minimum it would provide DCS capability.

5.3 EOS Transmitters

The present discussion on spacecraft transmitters addresses general technology in Section 5.3.1, the Mode II transmitter in Section 5.3.2, and the Mode I transmitter in Section 5.3.3.

5.3.1 Spacecraft Transmitter Technology

Research and development in the area of space communications transmitters aim at higher frequency and power. All solid state design is the immediate goal for vehicle transmitters (except for final power amplifiers above several GHz). Figure 5.3.1-1 gives an indication of the present state-of-the-art in spacecraft transmitters showing power out versus frequency. This figure indicates that at lower power and lower frequency ranges, solid state transmitters are preferred, whereas at high powers and primarily at higher frequencies, electron tubes (space charge and slow wave devices) are used. A major exception to this trend is when at lower frequencies (i.e., 1 GHz or less), it can become advantageous to apply traveling wave tubes (TWT) to provide a final output stage with either large bandwidth (10%) or high gain (40 - 50 dB) or both.



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Figure 5.3.1-1. Power Out Versus Frequency Trend

The choice of an RF source for a final power amplifier will naturally depend upon power requirements and operating frequency. For low power applications (i.e., 10 watts @ 1 GHz, 5 watts @ 2 GHz, 2 watts @ 5 GHz, less than 1 watt @ 10 GHz) solid state devices naturally are preferred. Above this trend line, it becomes necessary to resort to electron tubes for satisfactory performance. However, there are two types of electron tube devices capable of high power outputs over the range of 1 - 15 GHz (triodes/tetrodes and TWT's). The choice of a high power RF source depends mainly on the chosen frequency of operation. 2 GHz is approximately the cross-over point between space charge devices (triodes and tetrodes) and slow wave devices (TWT's and crossed field amplifiers) for higher power levels (above 10 w) and wider bandwidths (10% of operating frequency). There is no theoretical reason for not using slow wave devices at 1 GHz, however, the size of the device is large at this low a frequency. At this same frequency, the space charge device becomes more desirable. Therefore, the main emphasis of development programs for frequencies around 1 GHz and lower has been in triodes and tetrodes. This implies that the choice of the RF source may be relatively sensitive to small changes in operating frequency. At about 2 GHz, the TWT's are preferable and at 900 MHz, the space charge devices are an obvious choice. The intermediate frequency levels (1 - 2 GHz) represent some technological uncertainty.

Figure 5.3.1-2 shows the projection of the available power from triode/tetrodes and TWT amplifiers in various time frames for use in a satellite transmitter. TWT's at lower frequencies generally have not been developed, mainly because of a lack of demand. In addition, the large physical size makes permanent magnet focusing (necessary for low power drain) difficult at 1 GHz. Figure 5.3.1-2 does not include TWT's of high power since they require additional means of cooling (i.e., convection and liquid). These later higher power types would not be suitable for spacecraft application.

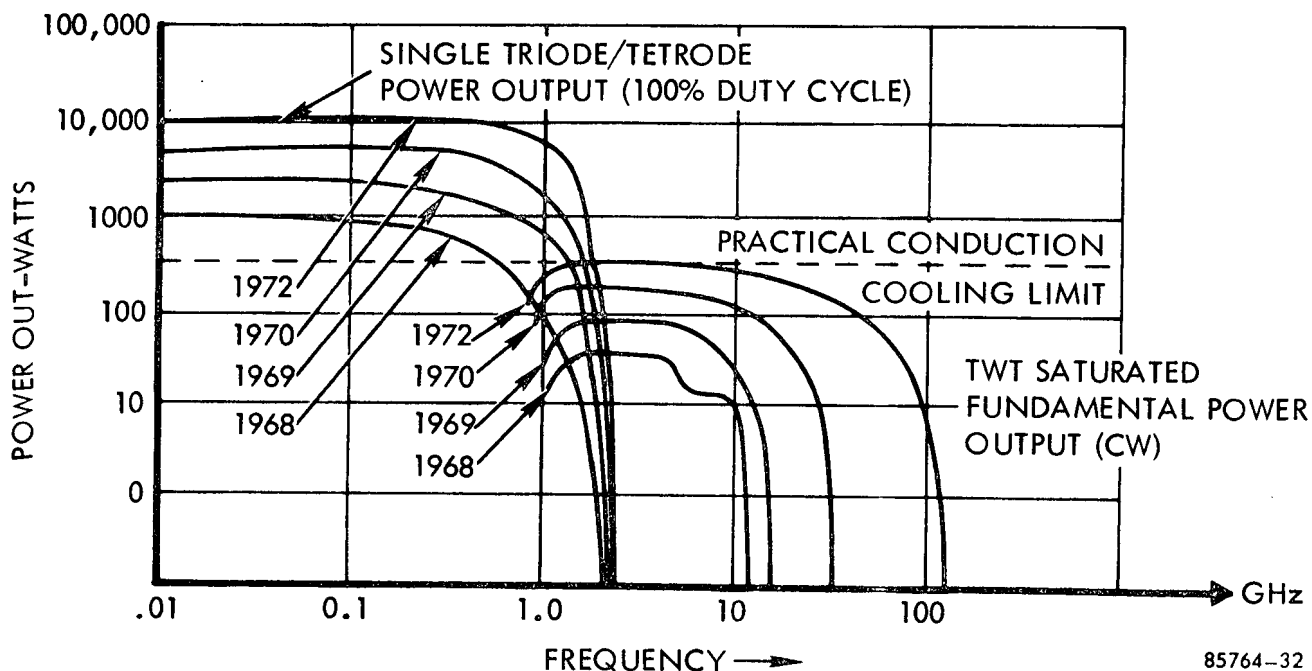


Figure 5.3.1-2. Electron Tube Comparison For Spacecraft Application

Another interesting high power tube technology is the crossed field amplifier that features low weight, high power and efficiency. An example of such a device is built by Warnecke Electron Tubes, Inc. which produces a 1 dW CW power output at S-band. However, at 1 kW it must be liquid cooled. 500w is achievable with conduction cooling.

The choice of a suitable power source may be influenced by the type of antenna used as well as frequency. For instance if the chosen frequency is around 1 GHz and an array antenna is used, it may be possible to use transistor power amplifiers to achieve the desired satellite ERP. A transistor power amplifier (10 watts) could be placed at each element of the array instead of lumping all of the power amp gain into a single element which then split feeds the power to each array element. Split feeding an array from a single power amp has the disadvantage that high power phase shifters must be used and the insertion loss of the phase shifting network degrades the output power level. On the other hand, RF transistors require high Q coupling circuits in order to match the inherently low impedance transistors to high impedance transmission lines. This makes the transistor amplifier bandwidth quite narrow.

As an inverse type consideration, the selection of a frequency of operation (within close limits) may be influenced by trade-off considerations aimed at reduction of the power amplifiers physical characteristics. As an example consider the possible choice between L-band and S-band as the boundaries within which a selection of operating frequency must be made. TWT's designed for operation over this frequency range vary in size from 2 to 200 lbs, depending upon gain and wave structure design. The selection of 1.5 GHz (L-band) at the required power will limit the tube to approximately 30 pounds and 30 inches in length, while selection of 2.5 - 3 GHz (S-band) would result in reduction of 25% in weight and size for the same requirement.

Other design tradeoffs can be made in the selection of a suitable power amplifier even after the frequency of operation has been selected. For example, TWT size is proportional to gain, therefore, an increase from 30 to 50 dB would result in an increase in axial length and some weight for the focusing magnets. A tradeoff could be made between high gain (50 dB) with the use of a solid state driver and lower gain with the use of a higher power driver to obtain the optimum package in size, weight and overall efficiency.

5.3.2 Mode II Transmitter

The baseline Mode II system will operate at S-Band with a 10 watt output power and an efficiency of approximately 25%. Transmission may be digital or analog FM. In either case the required RF bandwidth should be less than 10 - 15 MHz maximum.

Solid state 10 watt transmitters for Mode II transmission do not presently exist, while traveling-wave-tubes (TWT) have been used in similar applications. However, breakthroughs in semiconductor technology during the past year now permit the S-Band solid state transmitter to compete with the TWT at the 10-watt level in efficiency with a weight and volume saving. These 10-watt transmitters will probably be completed and space qualified within one year, and certainly for the EOS time period.

S-Band transmitters employing high gain, high efficiency, narrow band metal ceramic TWT's are available today in highly reliable space qualified packages. The DC/RF efficiency is 28 - 35% for a 20 watt version now being furnished on a SAMSO program. As an example of long life, units delivered for the USAF Comsat had lost only 0.3 - 0.5 dB after five years of operation, from a starting gain of 38 dB. Typical parameters for the Mode II TWT transmitter are:

Volume = 144 in³

Weight = 4 to 6 lbs.

Efficiency = 28 to 35% for TWT only, 25% including oscillator and modulator

In summary, beginning about 1972 - 73 space qualified solid state 10 wat S-Band transmitters will be available with efficiencies comparable to existing space qualified TWT transmitters; but with a weight savings of 1 to 3 lbs. per unit and a volume savings of more than 50%. One potential problem area which should receive further attention is the feasibility of operation in a linear (nonsaturated) mode with 25% efficiency and 10 watts output. Such linear operation is desirable if two carriers are utilized as when DCS and image data are transmitted simultaneously.

5.3.3 Mode I Transmitter

The baseline Mode I system requires a 10 watt Ku-Band transmitter with a bandwidth in the 1 - 1 GHz range. An efficiency of 25% or greater is desirable. Alternate frequencies of operation to the nominal 15 GHz are 8.5 GHz and 21.2 GHz.

Present technology dictates that the spacecraft transmitter utilize a traveling wave tube amplifier (TWTA). The TWTA can provide RF power outputs beyond one watt at the frequencies of interest, a feature not currently available with solid state power amplifiers. The RF output will be determined by the satellite prime power (40 watts DC nominal) and efficiency of the DC/RF conversion. In most applications where microwave amplifiers are needed; maximum efficiency is required. This is particularly true for spacecraft systems where primary power and weight requirements are extremely critical. It is a definite requirement, therefore, to operate these

amplifiers at or near their maximum output capabilities, i.e., in the saturated region. Typically, the overall efficiency of a TWTA, operating in saturation, including heater and voltage regulator, in the Ku-Band is 20 - 25%. Therefore, the assumed RF power output of 10 watts is not unreasonable.

As previously mentioned, the RF spectrum is becoming more crowded with advancing time and the only place to fit a new system into the spectrum is at higher frequencies. As frequency is increased, the dimensions of the tube must decrease. For the same power output level, the thermal loading of the TWT circuit is higher. This increased heating becomes a problem at higher power output levels and actually limits the power output capability of the tube.

Beside limiting the RF power output, the increased frequency of operation increases mechanical problems in assembling the tubes. For tubes in the 10 watt power output range, the relatively high voltage of operation creates a problem of voltage breakdown in the power supply and the TWT. Further development is required to alleviate these problems at high frequencies.

The reliability of TWT transmitters is extremely high, attested by performance data on existing lower frequency units.

The USAF Space and Missile Systems Organization and The Aerospace Corporation compiled data describing the TWTA performance of 26 orbiting satellites of the Initial Defense Communications Satellite Program (IDCSP) and the Despun Antenna Test Satellite (DATS). The tubes operate at X-Band with a 3 - 4 watt RF power output. As of October 1969, over 560,000 TWTA orbital operating hours had been accumulated. The overall TWTA mean time to failure (MTTF) was in excess of 47,000 hours with 90 percent confidence based on emission degradation failures.

5.4 EOS Antenna Systems

The command and tracking system antennas are beyond the scope of this study. However, unless packaging and mechanical problems are dominant there appears to be no reason not to utilize the ERTS A systems. Likewise, the ERTS A DCS antenna is appropriate. These choices are consistent with a philosophy of maximum utilization of existing and proven designs.

The approach for satisfying the Mode II requirement and various alternatives have been considered in Section 4.2.3.1. There a shaped beam technique which provides a gain versus angle distribution compensating for range variations is presented. The basic ERTS A antenna approach is applicable but with design modifications which take advantage of a reduced field of view to improve the link by approximately 3 dB. One possibility, if Mode II is to operate at S-Band, is to utilize a common antenna for Mode II and for telemetry and commands. This would eliminate one antenna and alleviate the mechanical and packaging problem.

A desirable feature for the Mode I system would be to employ a similar fixed beam antenna. However, this would result in a requirement for an extremely large antenna on the ground, the order of magnitude being 100 feet or so in diameter. Accordingly, one must consider a directive antenna to provide additional link gain. An antenna with a 5° beamwidth represents a reasonable choice with respect to the trade-offs between link gain, physical size, and pointing problems. Since this is a transmit only system, pointing must be programmed and thus requires accurate ephemeris and a stable orbit. With the ERTS vehicle this is the case.

The 30 dB gain which corresponds to a 5° beamwidth results in a very desirable and feasible ground antenna size. Reference is made to Section 4.1 which contains the link analysis. Thus, for the assumed situation in which there are to be multiple ground antennas throughout the world, the expense appears to be justified. Under the alternate assumption of a single (or a very small number of) ground antenna, it would be more cost effective to utilize a fixed beam antenna on the satellite.

The aperture size required to achieve the indicated gain is not in itself unreasonable. The size for each of the three candidate frequencies is given in Table 5.4-1. Pointing an aperture of this size presents no unrealistic mechanical problems and would not be expected to significantly perturb the orbit.

Table 5.4-1
Aperture Size for 30 dB Gain

Frequency (GHz)	Diameter (Ft.)
8.5	1.6
15.25	.9
21.2	.63

If the lower frequency should be selected, which is desirable from a performance point of view, the satellite aperture could be reduced with no impact on the ground because less rainfall margin is required.

Of course, utilization of a directive spacecraft antenna does preclude simultaneous reception by more than one receiving terminal. The area of ground illumination, assuming a flat earth model which is conservative, is approximately 44 miles at Nadir and 350 miles at the extreme pointing position of 60° off Nadir. There will be no application for which two terminals would be located in such near proximity.

In summary, the choice of a 5° beamwidth with 30 dB gain appears to be a good choice for the Mode I application. Various means for achieving this characteristic are possible and include a parabolic dish or phased array.

5.5 Data Handling and Multiplexing

A variety of multiplexing and data handling alternatives have been conceived during this study effort. The discussion here describes a likely configuration with considerable merit which has evolved. Following this description several alternatives or variations are also presented.

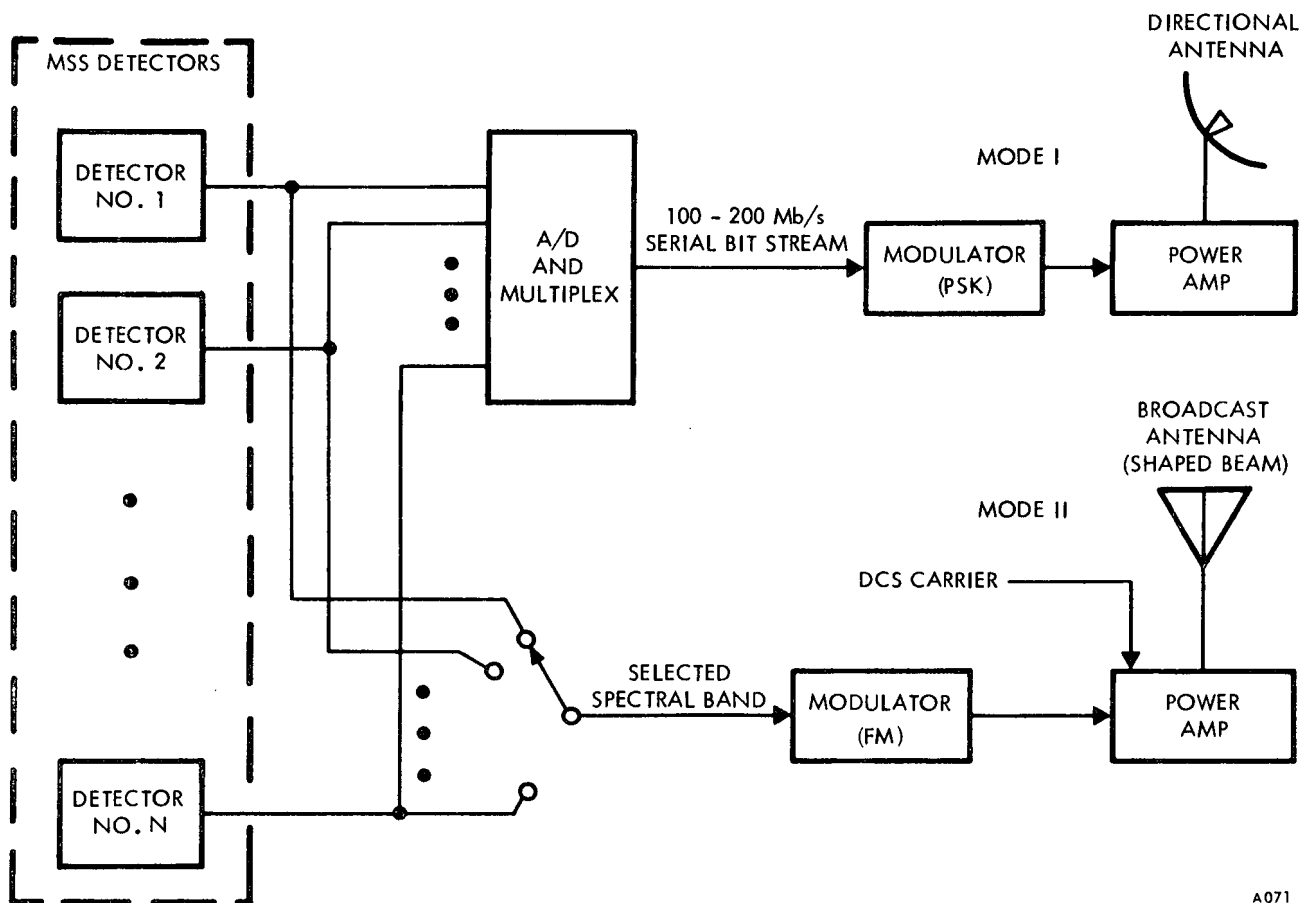
5.5.1 Baseline Spacecraft System

The most straightforward EOS data handling system for supplying the desired Mode I and Mode II data is depicted in Figure 5.5.1-1. The on-board sensor, a multispectral scanner, supplies video data via detectors which are active in a variety of spectral bands. To satisfy the Mode I needs which require all data produced, each individual signal corresponding to a specific spectral band is sampled in real time and a high speed multiplexer produces a single serial bit stream. The relatively low duty cycle, 65% on ERTS A, allows ample space for synchronization and formatting data along with any desired annotations such as ground position or calibration data. Refer to Section 6.2.5 for discussion of potential data formats and their utility.

The Mode II transmitter on the other hand has as its input a single spectral band signal which is selectable from the set of those available on command from the ground. The desired signal is coupled out of the MSS into the FM Modulator. Again the 65% duty cycle on the MSS allows insertion of any required framing or calibration signals. The system as conceptually described allows considerable flexibility for meeting the needs of diverse types of users.

Alternatively, the Mode II system may require digital transmission. This would reduce the modulator complexity and allow channel and/or source encoding schemes to be employed. The conceptual system approach to allow digital Mode II transmission is unchanged. The appropriate sampled signal would be selectable on command from the ground in this case.

Whether analog or digital transmission is utilized a number of processing steps are available and have been considered which reduce the transmitted information rate and therefore require less sensitivity on the ground. Assuming the basic MSS output is to remain unaltered (i.e., scan rate, etc. are constant), the information rate can be reduced by buffering, filtering to reduce resolution, grey scale reduction, or some combination of the above. Source encoding is another alternative and is considered in Appendix A. Extensive buffering requires a tape recorder and is not particularly desirable, especially for Mode I. Buffering can reduce the transmitted data rate for Mode II applications and result in 3-9 dB link savings. Likewise, on-board processing could be utilized for decision-making for the Mode II system to reduce the transmission rate by orders of magnitude. However, such speculation at this time has no firm foundation and is beyond the scope of this study.



A071

Figure 5.5.1-1. Image Signal Processing and Multiplexing

All things considered, it appears at this time as though a minimal amount of on-board processing is the best solution. As a minimum the information inserted into the scanner dead time intervals will provide basic identification, spacecraft position or time, and calibration data. Additional processing can be accomplished on the ground.

5.6 Spacecraft Parameter Summary

The parameter summary in Table 5.6-1 is a collation of performance requirements for the evolved system. Many alternatives are possible and have been discussed; however, the parameters given do represent a baseline system.

Table 5.6-1

Salient Parameters of Spacecraft Baseline Telecommunication System

	MODE I (To Regional Center)	MODE II (To Local User)
Data Source	Multi-Spectral Scanner	Multi-Spectral Scanner* (Single channel only)
Modulation Type	PSK	Analog FM
Data Rate	100 Mb/s	100-300 kHz
Type of Output Stage	TWT	Solid State or TWT
Power Out	10 watts	10 watts
Carrier Frequency	15.24 GHz	S-Band
DC/RF Efficiency	>25%	>25%
Antenna Gain	30 dB on-axis 27 dB @ $\pm 2.5^\circ$ **	-3 dB on-axis +3 dB @ $\pm 52^\circ$ **
Antenna Type	Parabola or Horn	Turnstile
Pointing	Program Track	Fixed Beam
Polarization	Circular	Circular

* May also include DCS data of comparative low rate

** Symmetrical Patterns

6.0

REGIONAL COLLECTION CENTER (RCC) CONFIGURATION

This section describes the design, performance, and estimated cost characteristics for the RCC which has evolved during this study effort. It is seen that the performance parameters used in the link analysis in Section 4.1 are realistic and achievable. In fact, the design as presented is conservative and there are potential cost saving trade-offs to be realized during any detailed design effort.

6.1

RCC General Characteristics

The purpose of the RCC is to receive, demodulate, and record high resolution, multispectral band image data which is gathered and transmitted from a satellite in a sun synchronous polar orbit. The RCC must provide maximum possible geographic coverage to minimize the possibility of a requirement for on-board storage. The stored data will be forwarded to a processing center which will produce the hard copy necessary for consumption by various users and experimenters. Implicitly, the processing center will perform registration, enhancement, false coloring, etc., which may be necessary.

A general block diagram of the RCC which illustrates the functional elements required to meet the stated requirements is presented in Figure 6.1-1. The subsystem can be grouped into major equipment categories of:

- a. Antenna Feed and Microwave Subsystem
- b. Antenna Pedestal and Reflector Subsystem
- c. Antenna Control Subsystem
- d. Receiver Subsystem
- e. Data Processing Subsystem
- f. Data Recording Subsystem

Design approach, performance characteristics, and cost estimates are presented for each of these groupings in Sections 6.2 and 6.3. A baseline system operating at 15.25 GHz is used for the discussion. Design characteristics would be similar at the other candidate frequencies of 8.5 and 21.2 GHz. However, as discussed, a cost differential could be expected with a cost savings realized at the lower frequencies.

The basic features of the system include a parabolic reflector with a DIELGUIDE feed providing high efficiency. A cooled parametric amplifier provides sufficient system sensitivity to allow desired performance of 10^{-6} BEP to data rates of 200 MB/s. A Pseudo-monopulse system provides accurate autotracking capability. Program and manual track modes are also available. The data is a serial bit stream with coherent PSK Modulation (or QPSK). Performance within 2 dB of theoretical is attainable. For the baseline system a magnetic recording technique is described. However, it is anticipated that alternate more effective approaches such as a holographic laser recorder will be available in the time frame of interest.

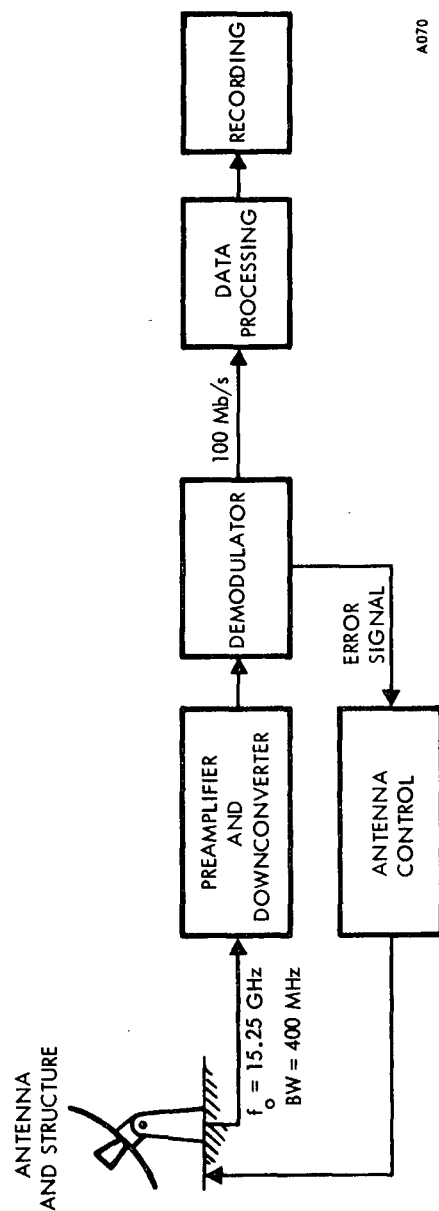


Figure 6.1-1. Regional Collection Center Functional Block Diagram

6.2 Subsystem Descriptions

Each of the six equipment groups is described in depth sufficient to show feasibility in the following paragraphs.

6.2.1 Antenna Feed and Microwave Subsystem

The antenna is a 16-foot paraboloidal reflector, with a high efficiency Cassegrain feed for Ku-band operation. Pseudomonopulse tracking is provided for circularly polarized signals over a 400 MHz bandwidth centered at 15.25 GHz. The feed subsystem, which included the feed horn, subreflector, dielectric guiding structure, and microwave components, is a scaled version of a feed previously built by Radiation for the AN/MSC-46 (MARK IB) System.

The feedhorn is a square, multi-choked design which provides optimum pattern shaping and low sidelobes for low noise temperature operation. The horn is fed by a four-element wave-guide cluster to enable formation of the monopulse tracking signals. Each waveguide channel contains a polarizer which efficiently processes the RHC polarized signals. The output from each of the four polarizers is delivered to a comparator, which generates the sum, elevation, and azimuth difference signals. The two difference signals are then processed in a ferrite scanner and combined with the sum signal in a directional coupler.

6.2.1.1 Antenna Feed

The feed is comprised of the horn, dielectric guiding structure (DIELGUIDE) and subreflector. The DIELGUIDE makes possible high antenna efficiency and low noise temperature by reducing spillover radiation and simultaneously creating a more-nearly uniform amplitude distribution across the subreflector.

The reduction of spillover radiation by the dielectric guiding structure is accomplished through the phenomenon of total internal reflection. When an electromagnetic wave passes from a medium of high dielectric constant to a medium of low dielectric constant at an angle greater than the critical angle, the wave is totally reflected. A diagram illustrating the principle of the guiding structure is shown in Figure 6.2.1.1-1. The DIELGUIDE requires a feed with axially symmetric patterns and constant phase center position. This is achieved by employing a square aperture pyramidal horn with corrugations. The design of the horn, DIELGUIDE, and subreflector is well understood and would require essentially no design risk.

6.2.1.2 Microwave Components

The microwave components are the components between the feed horn and the sum and difference outputs of the comparator.

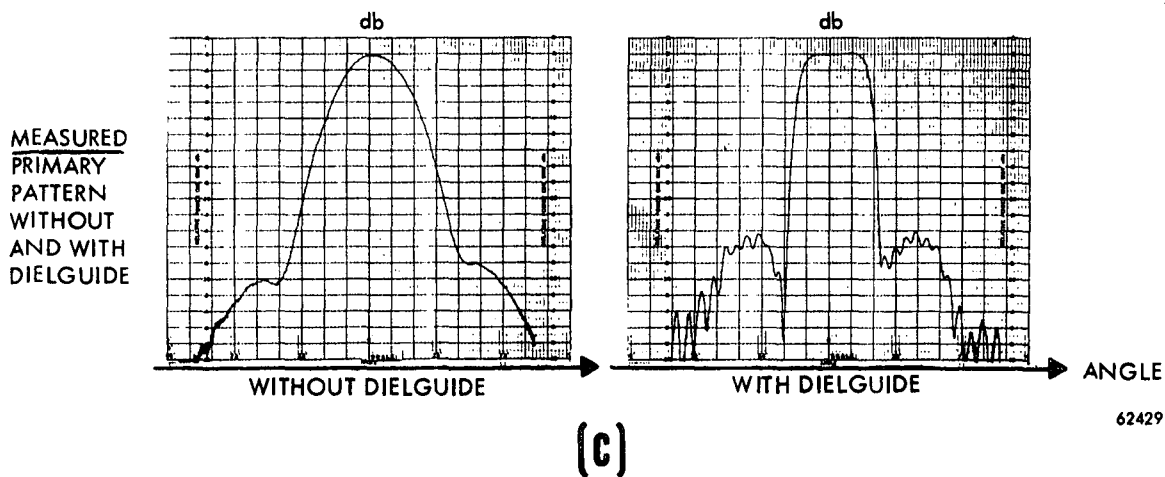
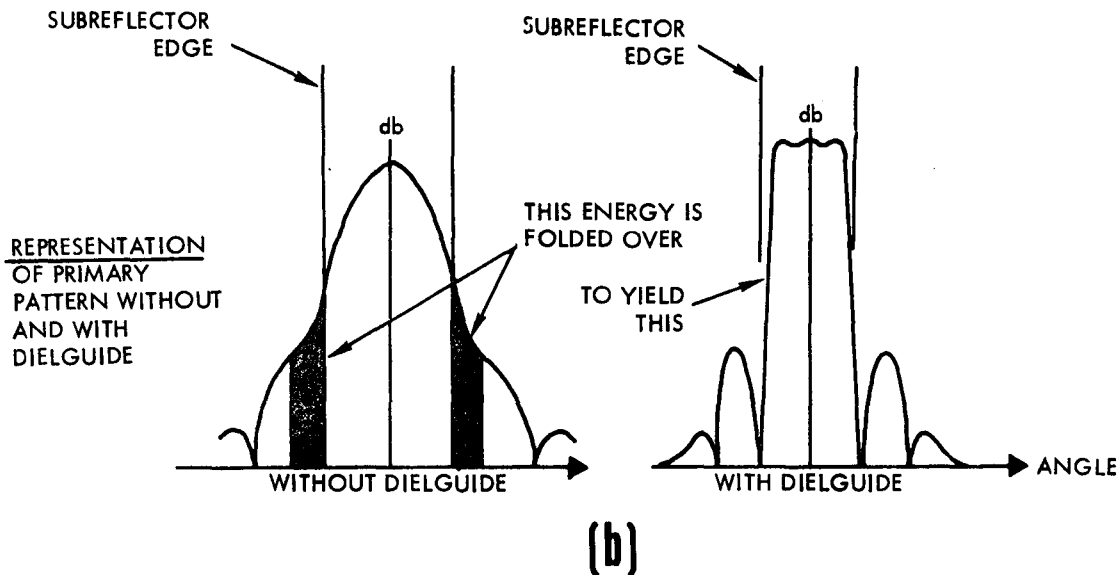
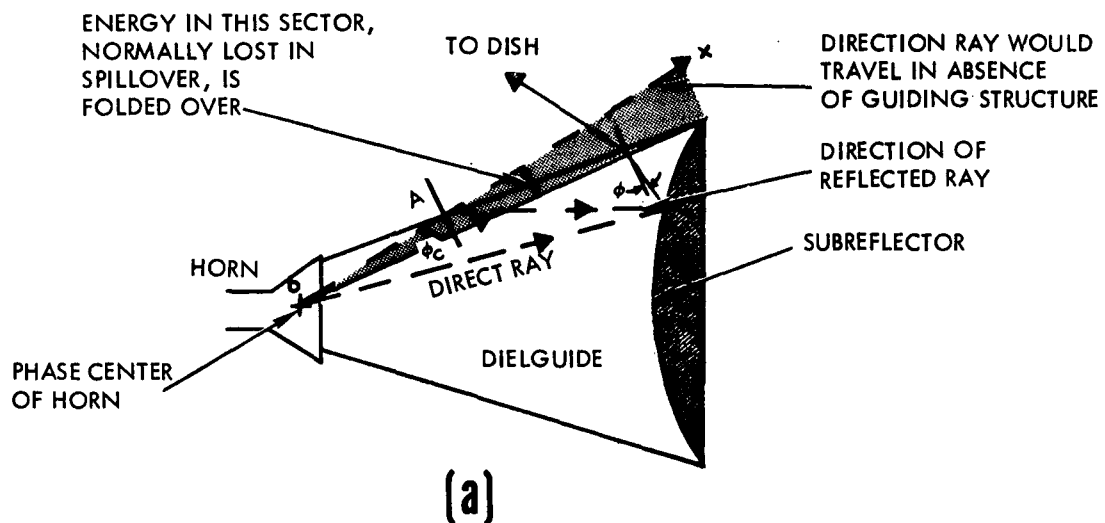


Figure 6.2.1.1-1. DIELGUIDE Principle of Operation

6.2.1.2.1 Phasing Section

The feed horn will cause phase dispersion between the E-plane and H-plane tracking modes since they have different propagation constants. If the dispersion is great and the tracking network phased to only one of the difference modes, the tracking performance will be degraded. Past experience has shown this dispersion to be 60° or more for the feed horn described. Since the two tracking modes have different phase velocities, a section of square guide is selected to increase the phase another 300° and put the two difference modes back in phase. The estimated loss for this section and the horn is a total of 0.007 dB.

6.2.1.2.2 Combiner

The combiner simply combines four widely separated pipes into four adjacent pipes that mate with the phasing section. The square pipes in the combiner are beyond cutoff for all modes but the dominant mode, and can therefore be bent without mode conversion occurring. The square pipe has a theoretical loss of 0.013 dB.

6.2.1.2.3 Waveguide Extensions

The extensions are used to stretch the feed out so that the maximum dimension of the orthogonal line comparator will comfortably fit within the proposed feed cone. The estimated loss for the section is .03 dB.

6.2.1.2.4 Polarizers

The polarizers are sections of iris-loaded square waveguide capable of producing an almost constant differential phase shift between orthogonal TE_{10} modes (polarizations) over a broad frequency band [26] . The irises look capacitive to one TE_{10} mode, causing a phase delay, and look inductive to the orthogonal TE_{10} mode, causing a phase advance. The size and spacing of the irises are selected to provide a 90° differential phase shift and a good match for both modes. Since circular polarization can be considered as the sum of two orthogonal linear polarizations of equal amplitude and 90° differential phase, the polarizers will convert received circular polarization into linear polarization.

The type polarizer with its inherent broadband, low loss characteristics has been successfully used on a number of satellite communications antenna terminals. The loss for this section is 0.12 dB.

6.2.1.2.5 Dual Mode Transducer

A dual mode transducer is provided to absorb all reflections which return cross-polarized. The loss of this component is 0.12 dB.

6.2.1.2.6 Comparator

The comparator is a four hybrid monopulse comparator which connects to the four rectangular waveguide outputs of the four duplexers. This comparator will be made up of folded H-plane and folded E-plane waveguide hybrid tees for optimum packaging, and will terminate in a sum channel output, an azimuth difference channel output, an elevation difference channel output and one unused port. A dummy load will terminate the unused port. The total loss in the comparator is calculated as 0.036 dB plus a 0.04 dB additional component in its entirety and is similar to those produced by Microwave Development Labs at other frequencies.

6.2.1.2.7 Pseudo-Monopulse Scanner Network

The scanner network connects the outputs from the comparator to the inputs of the preamplifier and converts the monopulse signals into sequential lobing signals (pseudo-monopulse). Figure 6.2.1.2.7-1 is a simplified scanner network diagram. The scanner configuration of two digital latching ferrite phase shifters of 0° and 180° relative phase shift connected by two 180° type hybrids was previously developed for the AN/TSC-54 (or MARK V) terminals.

6.2.1.2.8 Directional Coupler

The directional coupler, used for coupling the difference signals to the sum signal, is built in waveguide. This unit is a purchased item to furnished specifications. The sum channel insertion loss of this coupler is made up of $1/2 R$ loss in the conductors and coupling loss in the dummy load on the unused coupler port. The coupling loss for the recommended 13 dB coupler is 0.22 dB; the specified $1/2 R$ loss for the coupler is 0.08 dB.

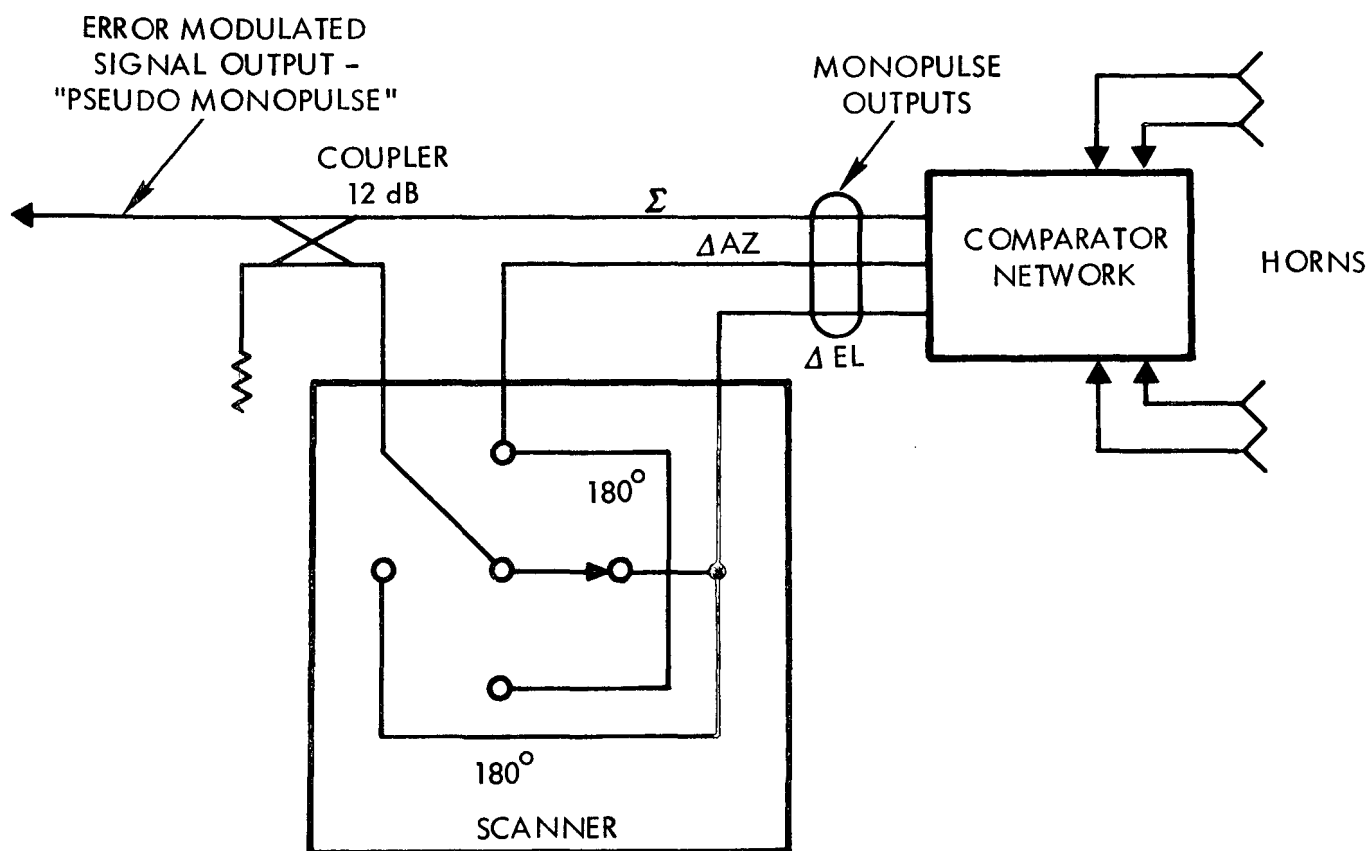
6.2.1.3 Antenna Performance

Major antenna performance parameters are estimated here and reveal the conservative nature of the link budgets.

6.2.1.3.1 Gain

The antenna gain can be determined by subtracting the losses noted from the theoretical area gain of a 16-foot dish operating at 15.25 GHz.

The antenna losses are summarized in Table 6.2.1.3.1-1. The area gain of the reflector is 57.9 dB. Thus the antenna gain measured at the feed output is 56.2 dB providing .6 dB margin from the value utilized in the link analysis.



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Figure 6.2.1.2.7-1. Scanner Network Diagram

Table 6.2.1.3.1-1. Summary of Antenna Losses

<u>Antenna Losses</u>	<u>Loss</u>
Illumination Efficiency - 77%	1.15 dB
<u>Components</u>	<u>Loss</u>
Horn and Section	.007
Combiner	.013
Extension	.030
Polarizers	.012
Dual Mode Transition	.012
Comparator and Unbalance	.080
Waveguide Runs	.060
Coupler 1 ² R	.080
Component Sub-Total	<u>.294 dB</u>
Coupling Loss	<u>.22 dB</u>
Total Losses	1.664

6.2.1.3.2 Noise Temperature

The antenna noise temperature at 10° elevation can be estimated assuming that approximately 7% of the antenna radiation is incident on the ground (300°K) and the remaining 93% is directed toward the Galactic pole (2°K). Of the 7% incident on the ground, 5% is direct feed spillover and 2% is due to secondary pattern sidelobes. These assumptions result in a computed noise temperature due to external sources of 23°K. Adding to this the excess temperature due to feed losses (0.3 dB), the total antenna noise temperature predicted is 44°K as measured at the feed output again showing a conservative link analysis.

6.2.1.3.3 Beamwidth

Experience with the DIELGUIDE Cassegrain feed in operational systems has shown the beamwidth to be given approximately by the following relation:

$$BW = \frac{63}{D}$$

Thus, at 15.25 GHz, the beamwidth is 0.26 degrees.

6.2.1.3.4 Sidelobe Level

Due to the nearly uniform aperture illumination, the DIELGUIDE feed produces a theoretical sidelobe level of -17.6 dB or 0.1318 relative voltage. However, the effects of blockage and reflector surface tolerances tend to increase this level. The increase in sidelobe level due to feed blockage is given approximately by [27] .

$$SLL = 1 - \eta_b$$

For this case, the increase is 0.013. Ruze [28] has shown that the increase in sidelobe level due to an rms surface tolerance of 0.1 radian (.013" at 15 GHz) in a reflector 100 wavelengths in diameter or greater is negligible. Thus, the expected sidelobe level is the sum of the basic sidelobe level plus the component due to blockage.

$$SSL = 0.1318 + 0.013 = 0.1448$$

which corresponds to a level of -16.8 dB. Experience has shown that scanning the beam, as proposed, generally raises the sidelobes by as much as 2 dB. Hence, the maximum sidelobe level would be approximately -14 dB, with a design goal of -14.5 dB reasonable.

6.2.2 Antenna Pedestal and Reflector

An elevation over azimuth axis pedestal supporting a sixteen foot diameter parabolic reflector is appropriate for the RCC ground station. The Cassegrain feed and subreflector are mounted in a support cone attached to the center of the reflector. The important features of the pedestal and reflector are described below.

6.2.2.1 Antenna Pedestal

One suitable antenna pedestal is a modified Model 8402 manufactured by Datron; Radiation is presently employing this pedestal on four high performance systems. The primary modification for this application would be the inclusion of dual drives, which is easily accommodated. The pedestal consists of three main elements; the elevation assembly, the azimuth assembly, and the riser base.

The elevation housing consists of a large stress-relieved structural steel weldment containing the elevation drives, data readout devices, and stowlock. It also serves as a mount for the elevation axis yoke and mechanical stops. The elevation axis drive gear reducers and data readout packages are mounted to the interior side wall of the tenance to the internal equipment areas. The elevation axis bearings are large diameter fourpoint contact bearings which fasten to either side of the elevation housing and mount the elevation yoke arms. The elevation drive bullgear is cut directly on the inside surface of the bearing inner race. The close coupling of this drive bullgear with the large diameter, moment supporting, elevating axis bearing assures a high degree of stiffness for the pedestal elevation axis.

The azimuth assembly consists of a stress relieved cylindrical steel weldment which houses the azimuth axis bearing. The inner race of this bearing fastens directly to the elevation assembly. The azimuth bearing is a large diameter, four-point contact, moment supporting bearing with the azimuth internal tool bullgear cut on its inner face. The azimuth drive gear reducer is mounted to the inner surface of the azimuth cylindrical housing and positions the elevation housing in azimuth.

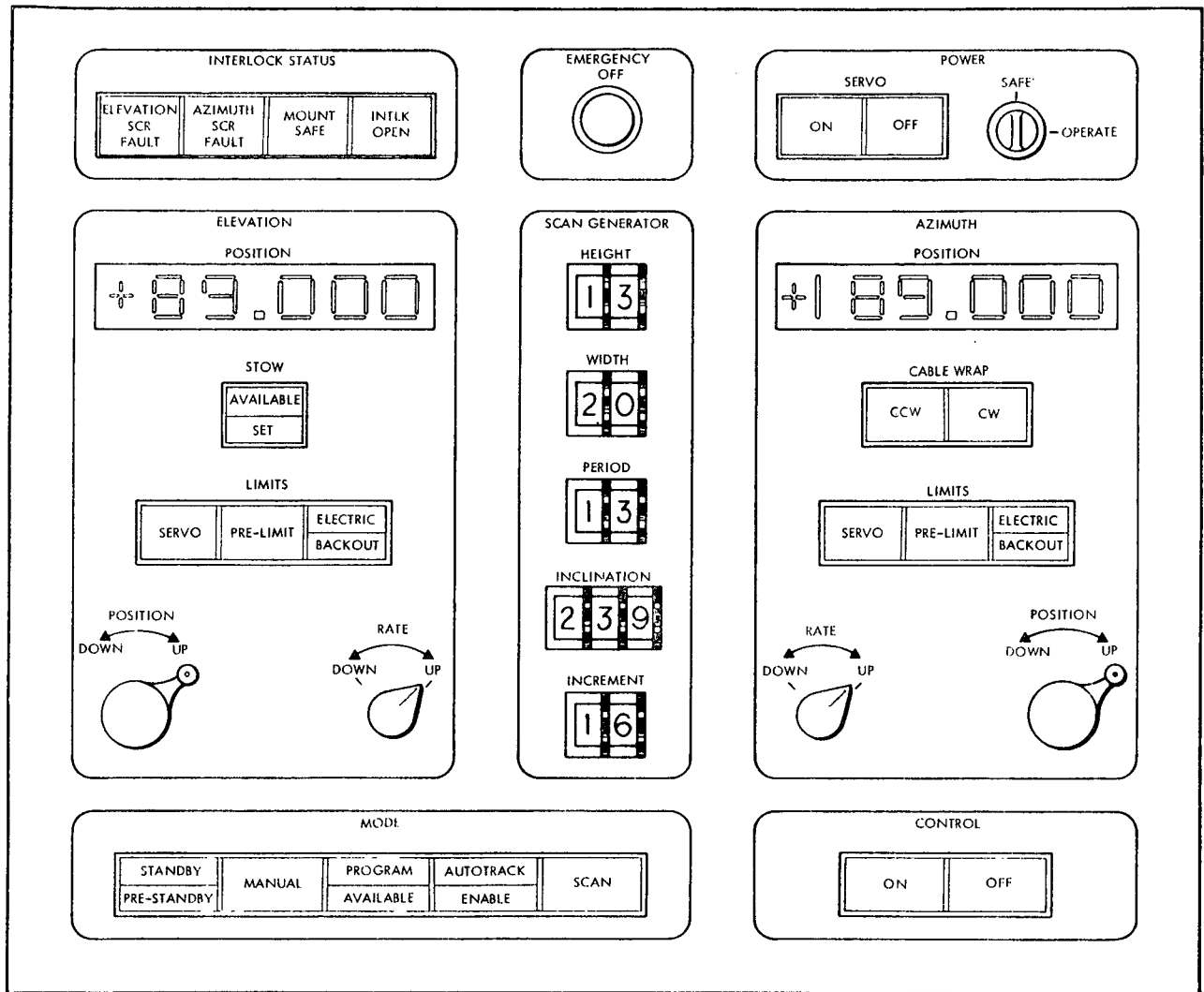
6.2.2.2 Reflector Assembly

The reflector proposed for this system is a solid surface paraboloid with a f/d ratio of 0.4 and a surface tolerance of 0.010 inch rms. The tentative supplier is Space Technology Incorporated. The standard high precision fabrication technique is presently being used on eight Radiation antenna systems. The reflector is basically a high strength sandwich shell with a polyurthane foam core and fiberglass reinforced epoxy skins. The reflective surface is an integral part of the antenna structure. The reflective surface is metallized with a flame sprayed coating .007 inch thick. A protective .005 inch epoxy skin covers the flame sprayed coating to insure maximum durability and long life for the reflective surface. The optimized structural use of light composite materials allow 25 to 50% weight reduction over any other product of equivalent performance. The foam and fiberglass construction provides the type of fabrication design which yields a high precision reflector at minimum expense.

6.2.3 Antenna Control Subsystem (ACS)

The Antenna Control Subsystem (ACS) consists of servo electronics, drive motors, a computer for antenna positioning, logic circuitry for mode control, and a centralized subsystem control and monitor facility. The servo design incorporates a position loop closed either through the tracking receiver or the programmer, a velocity loop with bandwidth selected for smooth tracking performance and several minor loops including a torque-limit loop and a torque-bias loop. The torque-limit loop reduces stress and wear in the motor drive trains by limiting motor torque to 100 percent overload. The torque-bias feature minimizes the position limit cycle produced by gearing backlash.

The human interface with the servo control and status functions is provided by the Antenna Control Panel (ACP), shown in Figure 6.2.3-1. Only those controls and indicators essential for operation during actual missions or in reconfiguration sequences are incorporated on the panel and are positioned for maximum operator convenience and comfort. The ACP and associated mode logic circuitry incorporate efficient internal automation techniques to minimize the role of the human operator and reduce the need for skilled, experienced operators.



A079

Figure 6.2.3-1. Antenna Control Panel

6.2.3.1 Mode Control

The mode logic is in complete command of the antenna servo and will provide all decision-making processes that determine which commands are applied to the servo electronics. In all cases, input commands are examined against the immediate servo configuration and the decision is made either to reconfigure the servo to accommodate the new mode selection or to reject the command. The mode logic, in making this decision, takes into account a vast number of predetermined priorities which will not allow the servo to be configured in an abnormal or dangerous combination of modes and submodes. The inputs of the limit switches are an example of those commands having the highest priority, overriding any and all other commands. This technique thus allows positive protection against even the inexperienced operator.

Antenna mode selection is made by manipulation of indicating push-button switches located at the antenna control panel. The six modes of operation available with this system are:

- a. **Standby-Pre-standby Mode:**
In this mode, the servo is held in true "standby" or quiescent condition with the brakes applied but with the system otherwise fully operational, preparatory to selection of one of the three following modes. If an emergency or an abnormal condition develops while the system is any mode, the system will revert to this standby condition but the "prestandby" portion of the control will be illuminated.
- b. **Manual Position Mode:**
In this mode, the antenna axes are positioned to the coordinates selected by the manual position handwheels.
- c. **Manual Rate Mode:**
In this mode, the antenna axes move with a velocity proportional to the magnitude of deflection of the rate knobs.
- d. **Program Mode:**
Selection of this mode causes the antenna axes to be positioned in response to an external program position command.
- e. **Manual Scan:**
In this mode, a sector scan generator shall provide a sine-cosine type scan pattern. The maximum height and width will be adjustable. The scan pattern can be rotated throughout 360 degrees through the use of the inclination control.

f. Autotrack Mode:

The antenna will automatically be reconfigured in this mode when autotrack is enabled and a phase lock indication is received from the receiver indicating the received signal characteristics are satisfactory. The antenna will then automatically track the error source.

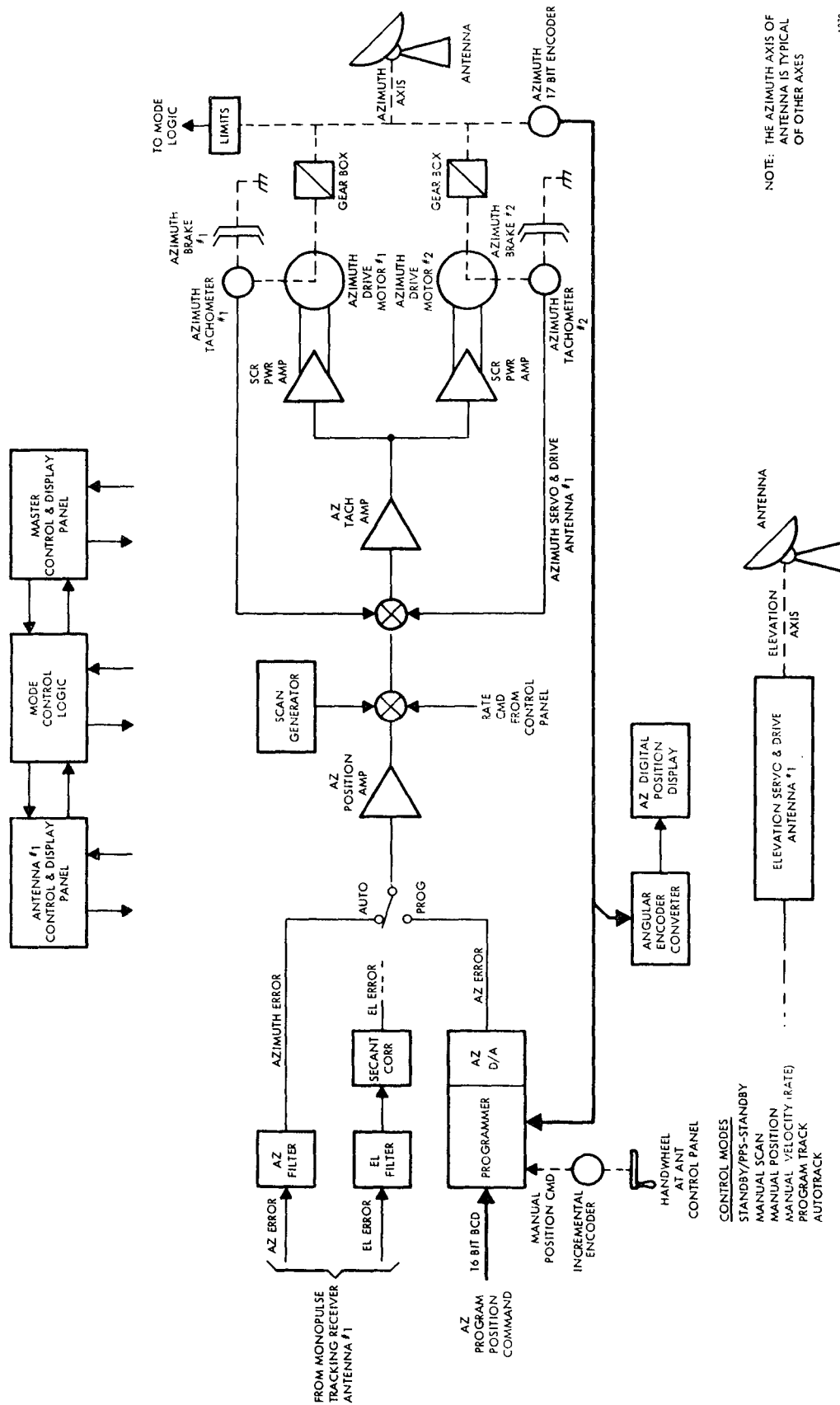
6.2.3.2 Control Loop Configuration

Figure 6.2.3.2-1 shows the block diagram of the control system. A current minor loop is used to introduce torque biasing to the system drive motors so that the gear train backlash is effectively eliminated from the system. The amount of preload or torque bias added to the drives is a function of commanded torque. At very low torque requirements, the bias added to the system is 10 percent of the rated torque. As the commanded torque increases, the bias is removed since there is enough preload due to viscous and coulomb friction so that backlash will not be felt. During a controlled shutdown of the drive motors, i.e., turning off the drive motor power from an operational mode, a 10 percent preload is first applied, the brakes are set, and then the drive power is removed. This ensures that the antenna will remain pointing to a fixed position with the system power turned off.

The SCR amplifier converts six phase ac power to fullwave rectified, bidirectional, dc power. The overall amplifier efficiency is greater than 98 percent. The ripple frequency on the output is six times the fundamental, and the output form factor is such that reactors are not required.

The following is a list of SCR amplifier features for the Servo Subsystem:

- The input to each SCR amplifier is through a differential input op-amp. This configuration effectively eliminates noise pickup on the input lines because of the high common mode rejection ratio of the op-amp (80 dB minimum).
- Each SCR amplifier has its own built-in power supply to prevent cross-talk on the power lines from one amplifier to the next.
- The amplifiers have a current feedback loop closure to force a linear gain throughout their full range.
- Current limit is adjustable and prevents the amplifier from damaging itself or the motor should the motor stall.



4078

Figure 6.2.3.2-1. Control Loop Servo Block Diagram

- The system includes switchgear functions, such as relays and rectifiers for motor brake operation, relays and rectifiers for motor field excitation, thermal sensors, cooling air sensors, etc.
- The Radiation-built six phase SCR amplifier has been very successful on many previous programs. Component failures have been nonexistent. The electronics are packaged on printed circuit cards and the cards plug into a card file. Only two adjustments are required for field alignment of the servo electronics.
- In comparison to a motor-generator set, SCR amplifiers are more efficient, smaller, lighter, less expensive, more reliable, and have a higher bandwidth.

6.2.3.3 Servo Electronics

All the servo electronics with the exception of the SCR circuits are housed behind the Antenna Control Panel. This line of electronics was developed by Radiation and has been used on several systems - both land based and shipboard. Maximum reliability is gained through the use of proven integrated circuitry while ease of maintenance is assured through accessibility, adequate test points, and the functional approach which is used throughout. All PC cards of the same part number are directly interchangeable as well as the SCR diode heat sink assemblies, thus further aiding maintainability.

6.2.3.4 Antenna Limits

The antenna is provided with both electrical and mechanical limits to preclude damage to the antenna structure or electronics as the antenna axes near the limits of motion. Four limits are provided: prelimit, servo limit, final electric limit, and the hydraulically buffered mechanical stops (in elevation only). The prelimit feature restricts the antenna velocity in the direction of the stop only at approximately two degrees before encountering the mechanical stop. The servo limit region is encountered after the prelimit and serves to prevent the servo from continuing to drive the antenna clear of the servo limit region. When the final electric limit is encountered, all drive power is removed and the brakes are applied. In the unlikely event that all of these limits malfunction, the mechanical stops will adequately arrest the antenna motion.

6.2.3.5 Servo Subsystem Performance

The drive motors have been selected to provide adequate torque for the worst case duty cycle. Each axis utilizes dual 2 horsepower, 1750 rpm motors (Nema

frame 186A which are designed specifically for high dynamic range and low speed-high torque operation. These motors are capable of moving the antenna at $1^\circ/\text{second}$ second acceleration and $10^\circ/\text{second}$ velocity.

The dual motors are connected in a torque bias configuration. The torque bias technique has been field proven by Radiation on the three 60-foot TT&C antennas for the SCF and one 150-foot antenna. In all cases, highly satisfactory results (which were predicted by preproduction computer studies) were achieved with no field redesign.

6.2.4 Receiver Subsystem

The major elements of the receiver subsystem are the preamplifier, down-converter, and demodulator. A low-noise 15.25 GHz parametric amplifier is recommended as the receiver preamplifier, followed by a downconverter which translates the signal to an intermediate frequency. Typically, the parametric amplifier and the downconverter are mounted on the antenna structure, as close as possible to the feed assembly to minimize microwave losses. The IF output of the down-converter is then conducted to the demodulator, located in an equipment building, by a relatively long run (perhaps several hundred feet) of low-loss coaxial cable.

The principle factors governing the front end design are bandwidth and noise temperature required for the acceptable bit error rate. Noise temperature obviously sets a lower bound on usable signal level, and the required receiver noise temperature is established by trading off noise temperature against transmitter power and antenna gains. Bandwidth is an important consideration in that too narrow a bandwidth ahead of the ultimate bit detection "matched filter" can cause intolerable degradation of bit error rate performance. The effective bandwidth ahead of the "matched filter" should be several times the bit rate, and the amplitude and group delay responses should be relatively flat over the frequency band occupied by the signal. These considerations are discussed in more detail below.

6.2.4.1 Noise Temperature

With regard to noise temperature, the primary contributor to receiver noise in a well-designed system is the preamplifier. The choice has been to two options insofar as the preamplifier is concerned: a cooled parametric amplifier or an uncooled parametric amplifier. The cooled amplifier offers considerable performance advantage, but at the penalty of slightly higher initial cost, more difficult installation, and considerably higher operation and maintenance cost. Thus, the operational cost factors influence the performance trade-offs and the final selection.

A noise temperature of 50°K or less is obtainable in a 15.25 GHz cooled parametric amplifier by conventional techniques in which the critical

components are cooled to a physical temperature of 15°K to 20°K . Three vendors (AIL, Comtech and CDC) are known to have built cooled units with noise temperatures of 40°K to 50°K at high X-band or low Ku-band.

In an uncooled 15.25 GHz parametric amplifier, a noise temperature of 400°K is readily achievable now, while noise temperatures of 200°K or less may be practical by the mid-seventies. The principal limitation in uncooled operation is the Q and selfresonant frequency of the varactor diodes, and experimental work is continually being done to improve diode performance. For example, AIL has built an experimental X-band amplifier with developmental diodes which has exhibited a noise temperature of 65°K at room temperature. The speed with which these experimental techniques are reduced to thoroughly practical and reliable amplifiers of moderate cost depends strictly upon the value of the market, and the market for Ku-band RF equipment is growing rapidly. In any event, an assumption of a 300°K noise temperature is probably quite safe for long-range planning and preliminary tradeoffs. This results in a 319°K equivalent noise temperature for the receiver subsystem which is less than that assumed in the link analysis by 0.4 dB.

6.2.4.2 Bandwidth

As mentioned earlier, the receiver front end components should be quite broadband compared to the bit rate for PSK modulation. A good rule of thumb is to use a predetection bandwidth four times the bit rate for NRZ coding or eight times the bit rate for split phase coding, with PSK modulation. Bandwidths chosen in accordance with this rule will sacrifice only a very small percentage of the signal energy and will cause negligible degradation of bit error rate performance.

The bandwidth-limiting component is the parametric amplifier. Mixers and broadband amplifiers for use in the downconverter are available with bandwidths in excess of 2 GHz. The parametric amplifier has gain-bandwidth limitations, however, and an instantaneous bandwidth of about 1000 MHz is the current state of the art for a multi-stage amplifier. For example, the practical "flat" gain-bandwidth product per stage, with double-tuned interstage networks, is only about 2000 MHz. Thus, only 6 dB gain per stage is attainable when the per-stage flat bandwidth is to be 1000 MHz, and only 2 dB gain per stage would be obtainable with a 1600 MHz flat bandwidth. Five stages would be required, as a minimum, for 30 dB gain with 1000 MHz bandwidth, whereas at least fifteen stages - clearly impractical - would be required for the same gain with 1600 MHz bandwidth.

It can be stated that an overall bandwidth of 800 to 1000 MHz for the receiver front end is practical. That would be comfortably wide for NRZ coding and would at least meet the minimum criterion for split-phase coding and the baseline

100 Mb/s data rate. Should the data rate increase to 200 Mb/s, the limited bandwidth available from the parametric amplifier is potentially another factor favoring QPSK, thus conserving spectral occupancy.

6.2.4.3 Electrical Configuration

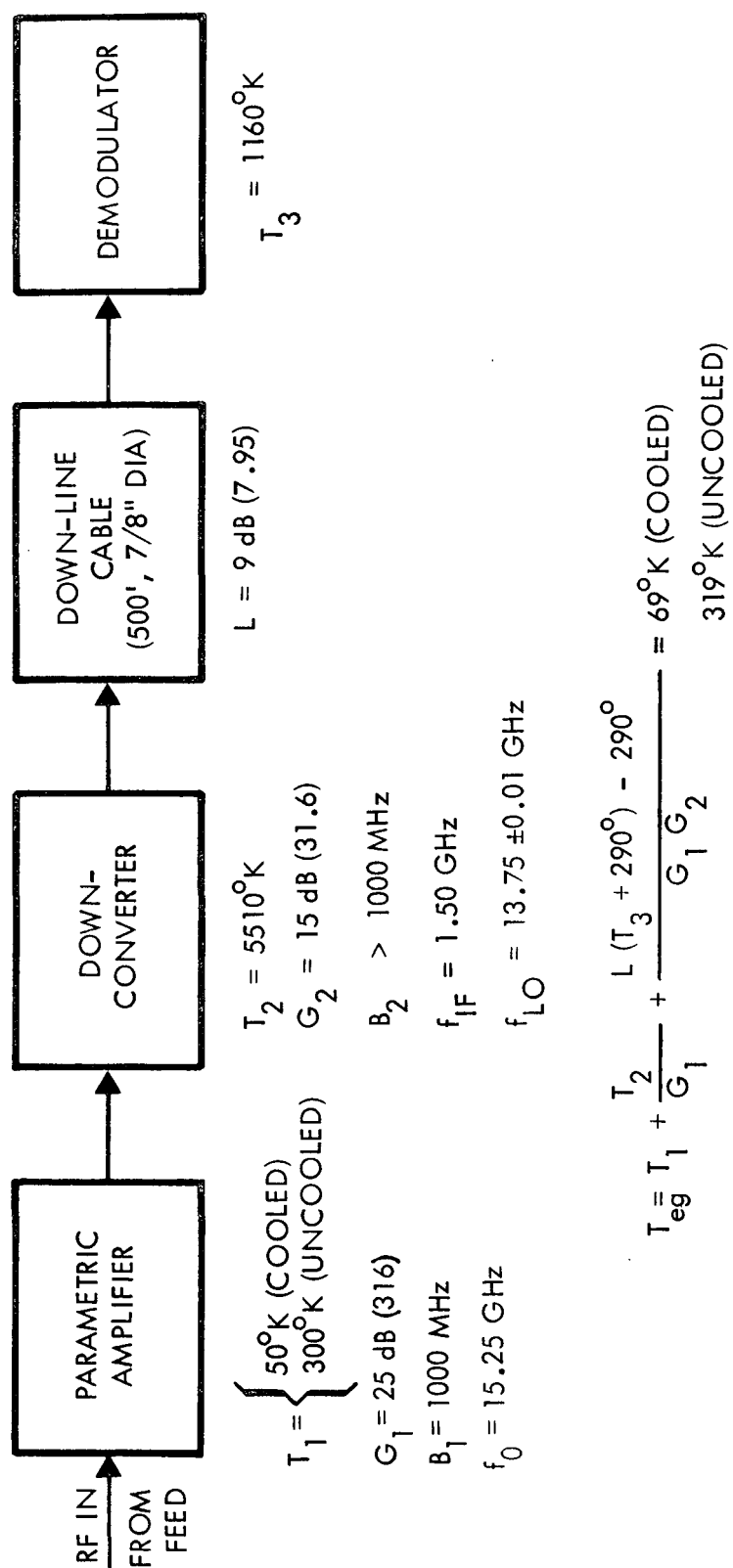
Figure 6.2.4.3-1 is a block diagram of a typical receiver configuration showing the gain distribution, noise contributions and other principle parameters.

The parametric amplifier gain and bandwidth are, respectively, 25 dB and 1000 MHz. A five- or six-stage amplifier will meet these requirements. As for noise temperature, 50°K is assumed for a cooled amplifier and 300°K for an uncooled amplifier. Although a higher amplifier gain than 25 dB is feasible, this value is a good compromise between dynamic range and a minimization of subsequent noise contributions. Linear operation of the parametric amplifier and succeeding stages can be expected for input signal levels of -40 dBm or less.

Primary considerations in the downconverter are IF center frequency, noise temperature and gain. An IF center frequency of 1.5 GHz is a good selection, since broadband amplifiers are readily available with flat bandwidths from 1.0 to 2.0 GHz and noise figures of less than 6 dB. A noise temperature of 5510°K (13 dB noise figure) is budgeted for the downconverter; this figure allows for a mixer conversion loss of 6.5 dB, an IF preamplifier noise figure of 5.5 dB, and combined losses of 1 dB for ferrite isolators at the input and output of the mixer. An overall downconverter gain of 15 dB is compatible with minimizing subsequent noise contributions and preserving the dynamic range established by the preamplifier. The local oscillator is a solid-state fundamental-frequency cavity oscillator. Its nominal center frequency is 13.75 GHz, and a tolerance of ± 0.01 GHz allows for frequency drift due to temperature changes and aging.

A nominal loss of 9 dB is allocated for the down-line cable, corresponding to 500 feet of 7/8" diameter low-loss coaxial cable.

The demodulator is assumed to have a noise temperature of 1160°K , which corresponds to a 7 dB noise figure. In the time frame of interest PSK and QPSK demodulators will be available for data rates of 50-200 Mb/s. A number of vendors are currently developing equipment for high rate requirements and repeatable production will be possible within the 1972 time frame. Actual cost in implementation for the present application is dependent upon the demand and associated development during the next 2-4 year period. Recurring costs are essentially constant over the data rate range of interest and are also independent of the PSK versus QPSK factor for the demodulator itself.



86282 -21

Figure 6.2.4.3-1. Block Diagram of 15.25 GHz Receiver Front End

As an example which lends confidence to these statements, Radiation has demonstrated a 400 Mb/s QPSK modem with performance near theoretical predictions, and presently has a 1 Gb/s unit undergoing tests.

The receiver subsystem also provides the demodulated error signals out for input to the servo system. The elements required for this function are well known and present no design risk.

6.2.4.4 Physical Configuration

The parametric amplifier and downconverter, as mentioned before, are mounted on the antenna back-up structure as close as possible to the feed and are connected to the demodulator by a long coaxial cable. There is also a remote control panel located in the equipment building, with power and control wiring linking it with the parametric amplifier and downconverter. For the case of the cooled parametric amplifier, there is a helium compressor, mounted on a platform below the antenna elevation axis, with associated helium lines.

The parametric amplifier along with its cryogenics and local control and monitor facilities, is mounted in a single enclosure. If it is to be exposed to the weather, a removeable weatherproof enclosure is furnished to protect against moisture, dust, salt spray, etc. The parametric amplifier size and weight are typically 2' x 2' x 3' and 65 pounds, respectively, for a cooled unit and considerably less for an uncooled unit. Its RF interfaces are by means of WR-62 or WR-75 waveguide flanges, and the power and control interface utilizes one or more MS connectors. A cooled amplifier also has a high-pressure helium input connection and a low-pressure output connection.

The downconverter may either be mounted in a weatherproof enclosure or on a plate, depending upon the environment. A typical plate-mounted unit weighs about 8 pounds and measures approximately 10" x 8" x 4". An enclosed unit has a size of about 12" x 12" x 5" and weight of about 15 pounds. A WR-62 or WR-75 waveguide flange is used for the RF input and a coaxial jack, typically Type N, is used for the IF output. The power input is an MS connector.

A potential helium compressor for cooled application is a CTI Model 350 which has universal usage. It is shock-mounted on a platform such that it has free air flow on all sides and remains within $\pm 10^\circ$ of a horizontal attitude at all times. It has a size of 15-1/2" x 25-1/2" and weighs about 175 pounds. The helium output goes through a high-pressure line to the parametric amplifier, and the return is a low-pressure line. The power input is 230V, 47-63 Hz at 2.1 kW.

The amplifier remote control panel mounts in a standard 19" rack in the equipment building. Control and monitor facilities are provided for main power, amplifier internal temperature (cooled units only), dewar vacuum (also cooled units only), pump-power, and pump klystron elapsed time. The panel has a height of 5-1/4" or 7" and weighs 30 pounds or less.

6.2.5 Data Processing Subsystem

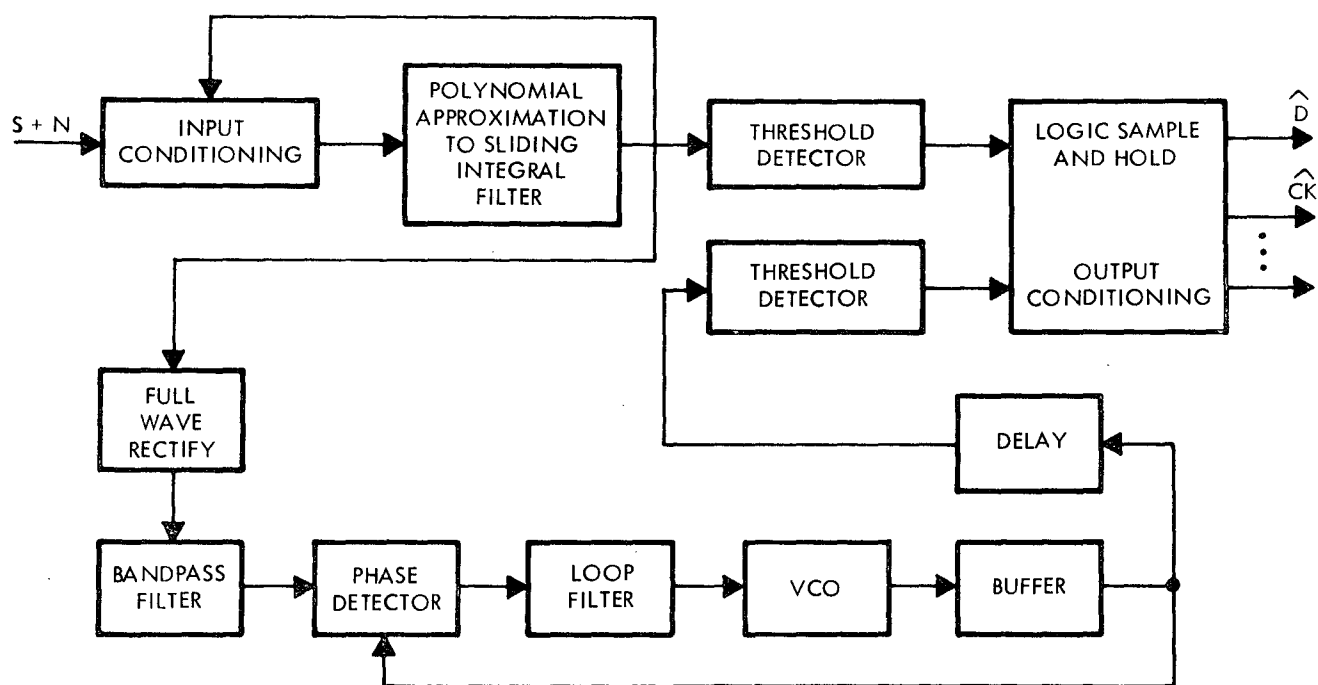
The data processing of concern consists of bit synchronization and signal conditioning along with group synchronization and decommutation. Additionally, special processing might be utilized to extract specific portions of the data for immediate study or to insert annotation data or station timing for eventual utilization in registration or other computational aspects. These factors are addressed individually below.

6.2.5.1 Bit Synchronizer - Signal Conditioner (BSSC)

The BSSC in the RCC must provide serial data detection in the range of 50 - 200 Mb/s. It is desirable that near theoretical performance be achieved by the BSSC since the link has been sized assuming a maximum of 2 dB implementation loss.

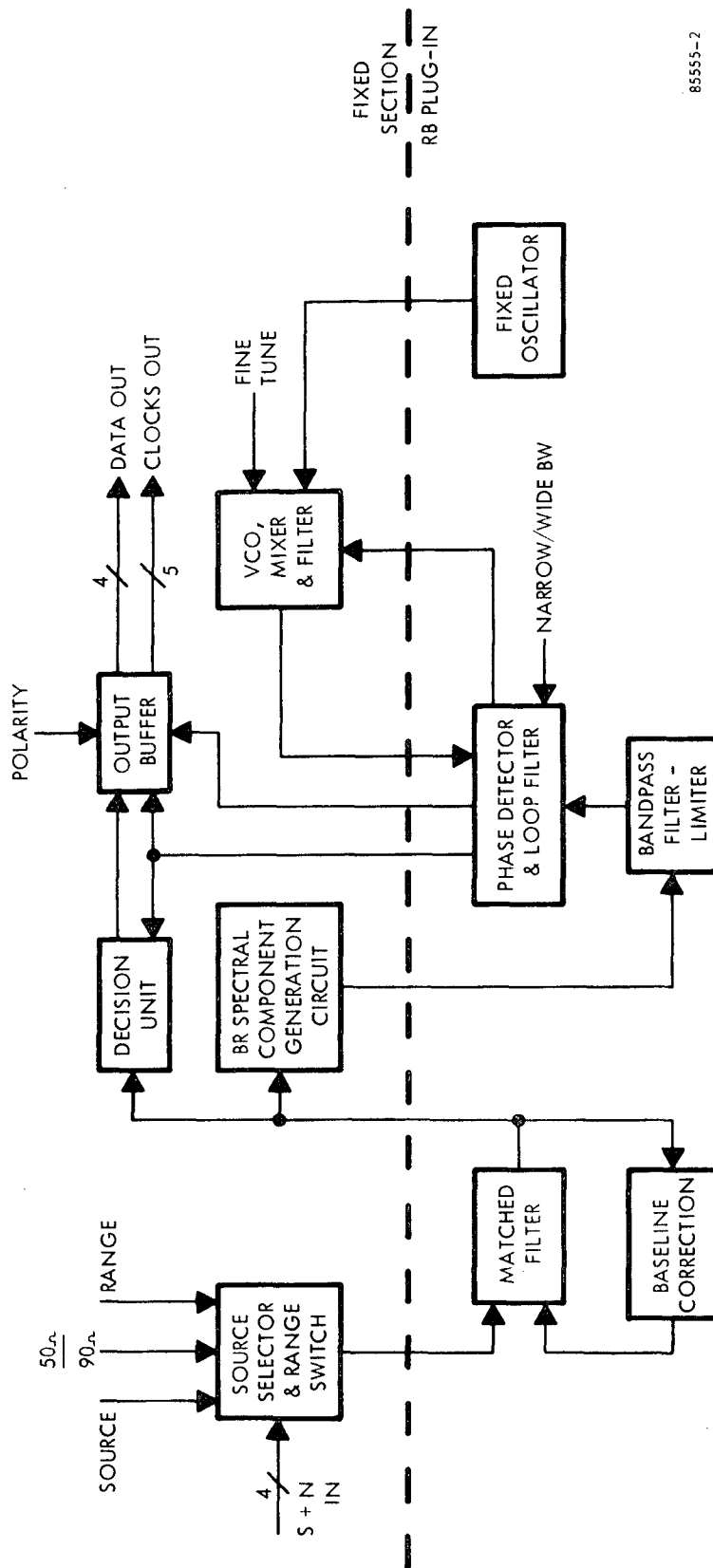
Systems operating at the 200 Mb/s speeds are mainly confined to the laboratory at the present time. Although many vendors claim equipment operating at these speeds, there are extremely few published examples of good system performance. Radiation does have equipment at these speeds, operating with excellent performance. This is demonstrated by the published work found in Reference [20]. Because of this previous work, Radiation is in a position to develop accurate cost information for these system elements.

For a discussion of performance versus complexity and cost-effectiveness among different techniques for implementing signal conditioning and bit synchronization in the bit rate range from 10 to 200 Mb/sec, see Reference [20]. With several techniques, performance within 1 dB of theoretical is achievable at both 50 Mb/s and 200 Mb/s. A block diagram of the BSSC implementation considered most cost-effective for both bit rates is given in Figure 6.2.5.1-1. At 50 Mb/sec such a BSSC exists as a Radiation standard product BSSC which operates at any bit rate from 1 Mb/s to 75 Mb/s by means of plug-ins. The exact block diagram for this unit is given in Figure 6.2.5.1-2 and a photograph of the unit is given in Figure 5.2.5.1-3. Options for quadrature PSK operation and multilevel decisions are available. This hardware has been delivered to NASA on contracts NAS5-20194 and NAS9-10441. For 200 Mb/sec operation similar hardware exists as laboratory equipment. In Figure 6.2.5.1-4 a photograph of a Radiation 200 Mb/sec demonstration BSSC is presented. Hardware



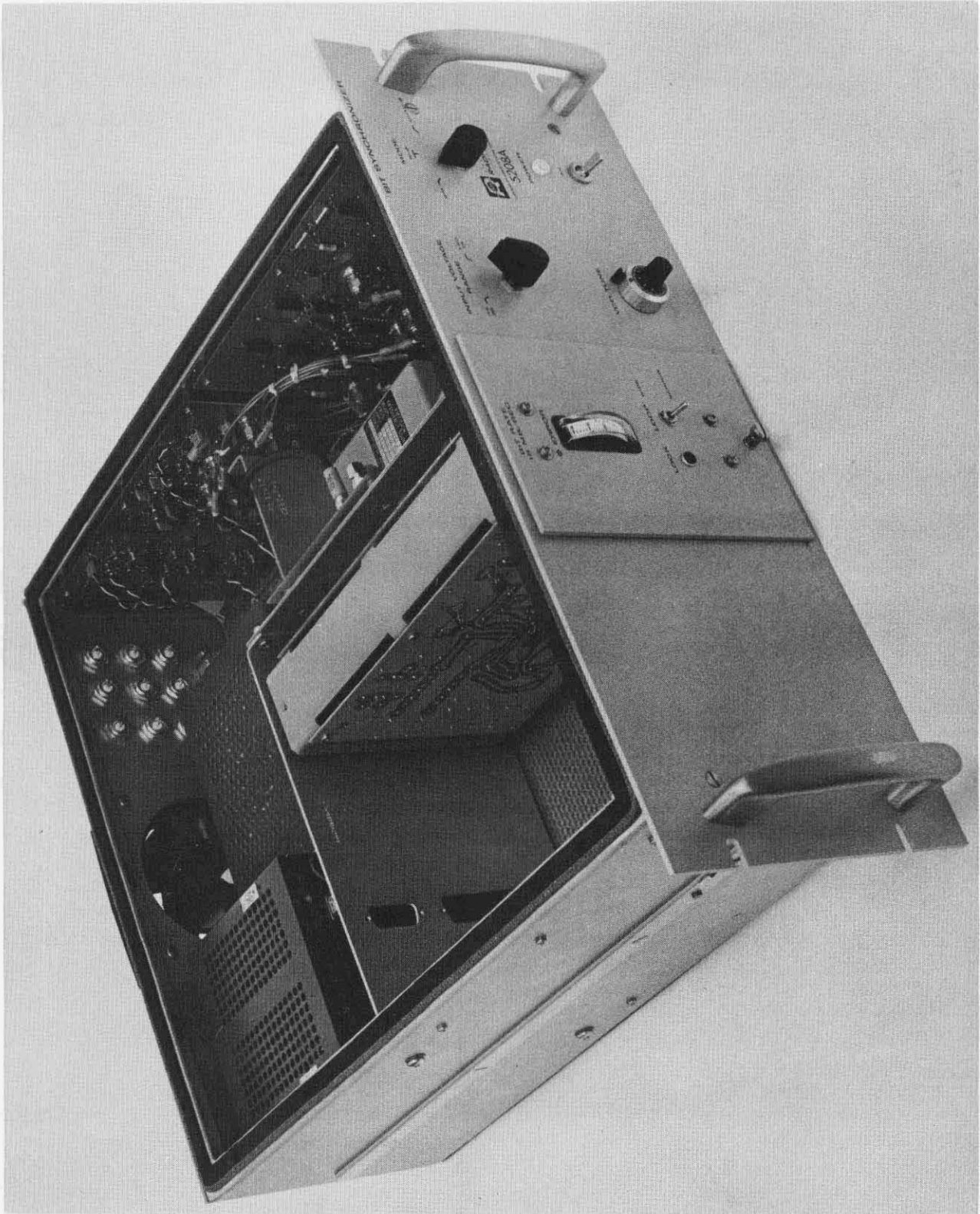
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Figure 6.2.5.1-1. BSSC Block Diagram



85555-2

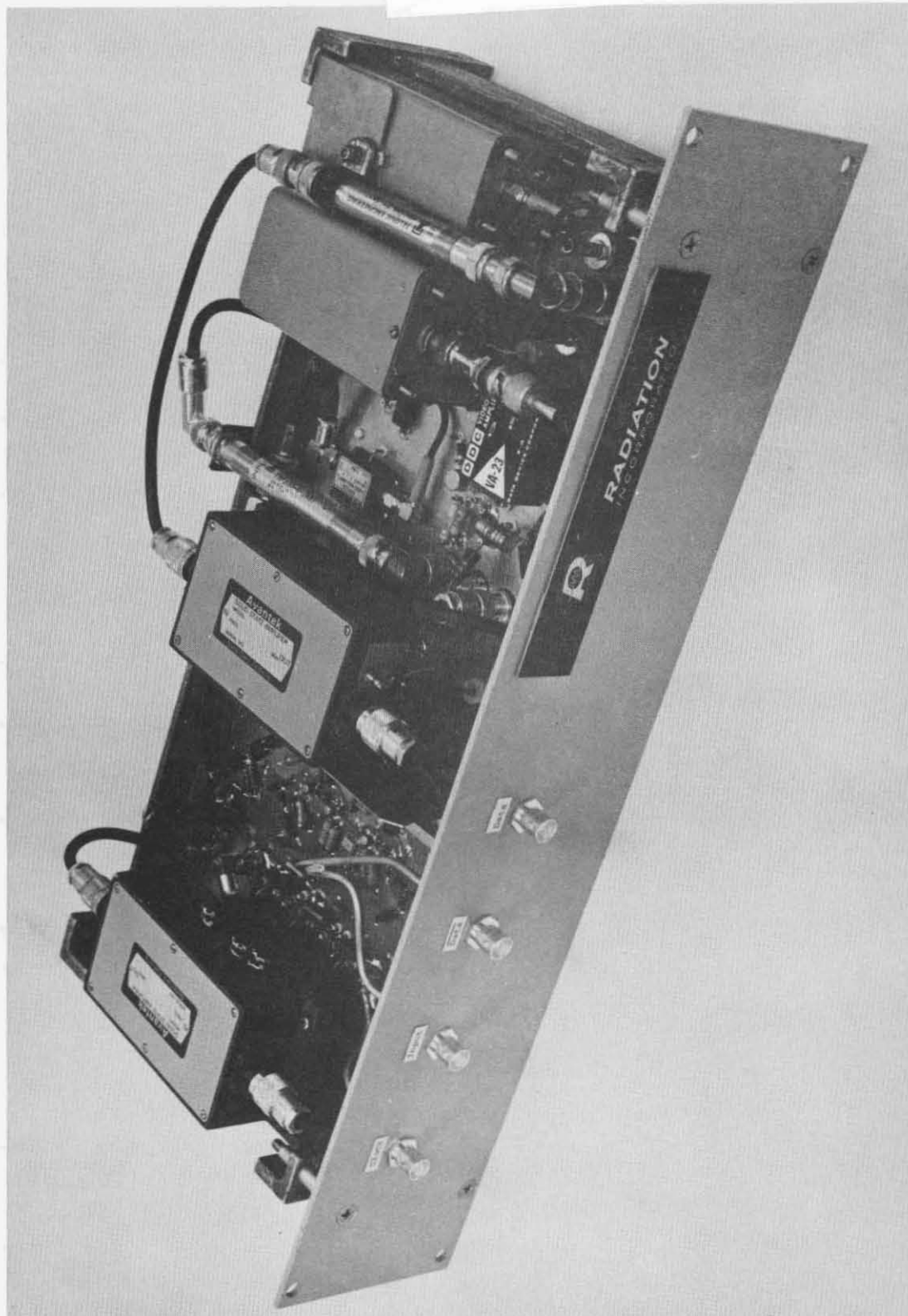
Figure 6.2.5.1-2. 1-75 MBPS Standard Product BSSC Block Diagram



70-1885

Figure 6.2.5.1-3. Bit Synchronizer

NOT REPRODUCIBLE



70-1890

Figure 6.2.5.1-4. 200 Mb/s Lab BSSC

of this type should be delivered on several programs in the near future. The ITC paper in Reference [20] gives an overview of investigations to 200 Mb/sec. It should be noted that the next phase of investigation has been initiated and covers the 200 Mb/sec to 1 Gb/sec bit rate range. A BSSC operating to 500 Mb/s should be available in 1972.

For these reasons the BSSC is considered a no risk item.

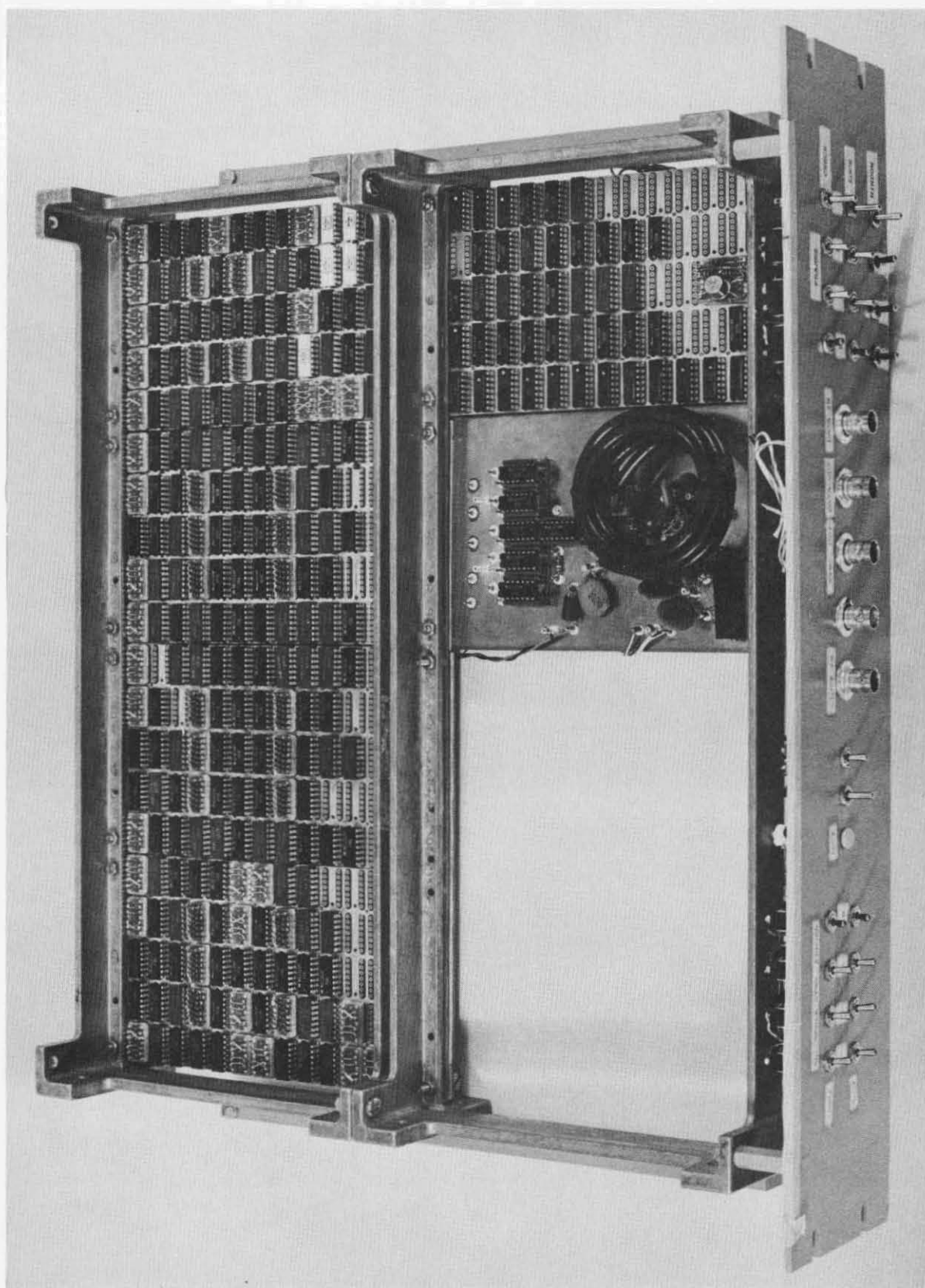
6.2.5.2 Group Synchronizer - Decommutator (GS-D)

As with the BSSC type equipment discussed in the previous section, there presently exists little off-the-shelf equipment for group synchronization and decommutation. However, Radiation has developed this capability and can provide both performance and costing data based upon fabricated and tested hardware.

Implementation of group synchronization and decommutation at bit rates from 10 Mb/sec to 200 Mb/sec is covered in the paper in Reference [20]. For GS-D implementation at 50 Mb/sec on all digital GS-D is recommended. This can be cost-effectively implemented at 50 Mb/sec with 4 nanosecond emitter coupled logic (ECL) on backplane wire-wrap boards. The group synchronizer-decom strategy can be programmable and the same as any presently available implementation. Radiation has computer programs allowing the performance evaluation of any particular strategy. With the advent of Shottky TTL and the growing number of available logic functions, a trade-off study of cost versus performance should be made between TTL and ECL at the time of implementation. A group synchronizer implemented with 4 nanosecond ECL on backplane wire-wrap boards and operating to 40 Mb/sec has been delivered to NASA on contract NAS5-20193. A picture of a similar all digital laboratory group synchronizer operating to 50 Mb/sec is given in Figure 6.2.5.2-1. To achieve operation at 200 Mb/sec, a mixed analog-digital approach is required. The correlators in the group synchronizer are analog while the rest of the group synchronizer is implemented with 1 nsec ECL on two layer PC boards with stripline interconnects. If at least four bit syllables are used, then a processing rate of greater than 50 Mb/sec is required. Thus, 4 nanosecond ECL on backplane wire-wrap boards can be used to implement the decommutator. In Figure 6.2.5.2-2, a picture of a laboratory demonstration group synchronizer-decommutator operating to 200 Mb/sec is given. As sub-nanosecond logic with higher toggle frequencies progresses, the cost-effectiveness and feasibility of implementing the correlator digitally should be examined.

6.2.5.3 Data Format

A decommutator for the RCC which demultiplexes the baseline 100 Mb/s serial data stream into its constituent channels has been recommended. The major



70-0524

Figure 6.2.5.2-1. 50 Mb/s Lab Group Synchronizer

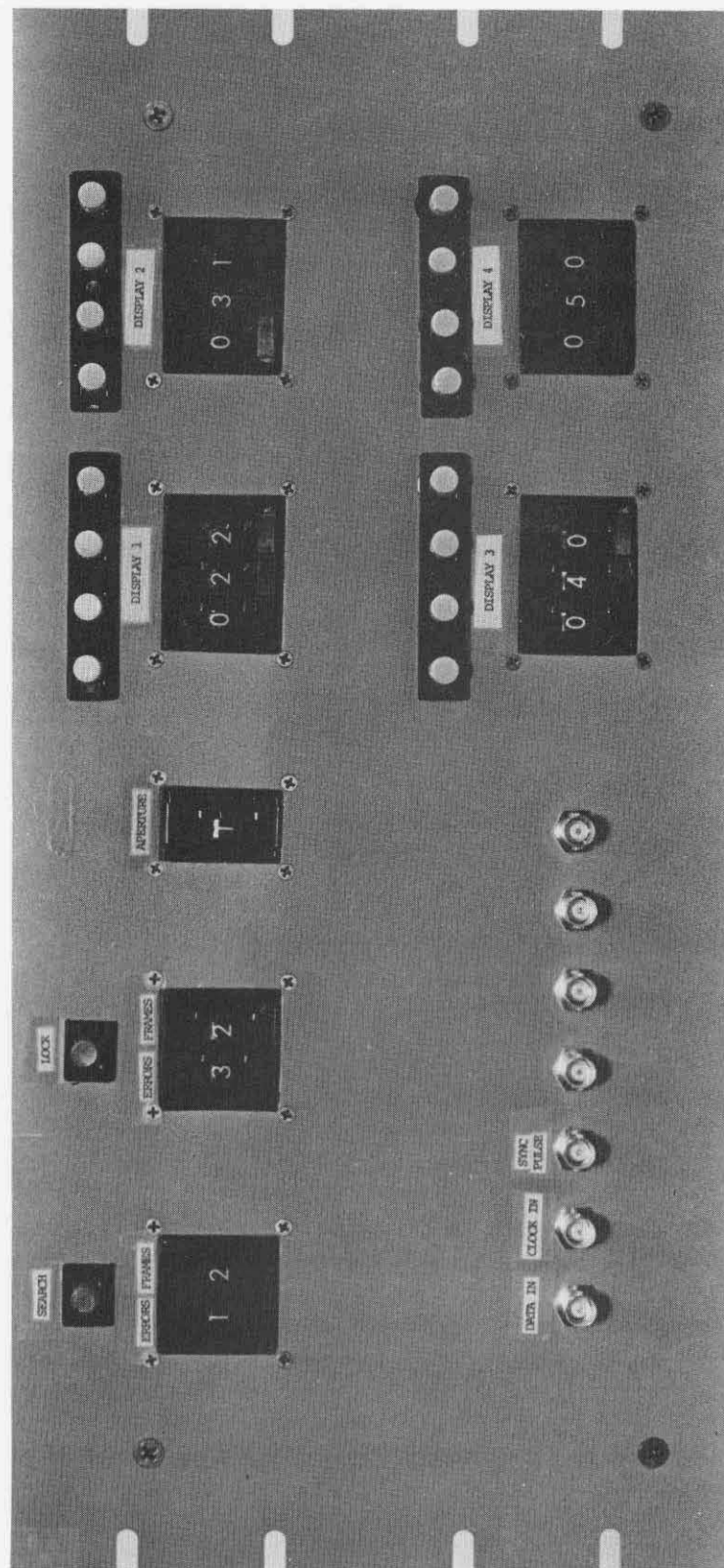


Figure 6.2.5.2-2. 200 Mb/s Lab Group Synchronizer

reason for this recommendation is to simplify the recorder subsystem required. Generally, it is more straightforward to record and reproduce a few lower rate channels (for example 4 - 25 Mb/s signals) than to record and reproduce the equivalent composite. If there is no requirement to ever reconstruct the original high rate signal, the associated timing problems can be avoided in this manner. This channelized method is especially appropriate for magnetic and holographic recorder approaches.

A standard approach appears appropriate for formatting the high rate serial stream. Insertion of a group sync word periodically in the data provides for the decommutation process. The trade-offs of acquisition time versus word length versus false alarm rate, etc. are discussed in Reference [29] . It should be noted that, without buffering, the sensor duty cycle conveniently allows insertion of suitable group synchronization patterns along with other relevant data. This data could include sensor status information, spacecraft orientation signals, or other data useful for ground signal processing.

In addition to the group synchronization pattern in the multiplexed data, it will be desirable to insert synchronization and overhead bits into the channelized signals. At a 25 Mb/s rate on each channel (each channel corresponds to a spectral band), there are on the order of 6000 samples per scan line or 36×10^3 bits/line for 6 bit samples. It would be difficult to maintain absolute synchronization through this number of bits. This problem can be alleviated by utilizing a synchronization pattern inserted periodically in each scan line for each channel. Each channel could use a unique pattern orthogonal to the other spectral band channels to facilitate identification if that is required. Thus, the synchronization patterns would divide each line scan into segments of around 4 or 5 mile widths each. This is accomplished by a nominal 30-bit pattern approximately every 1500 data bits which is a good ratio of sync to data. This is indicated below.

Group Sync 30 bits	Line Count 10 - 15 bits	Segment Count 5 bits	Data 1500 bits	Group Sync 30 bits
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The format illustrated also provides for simple registration between spectral bands and/or for easy extraction of selected data from within the 100 mile scan line. The 10-15 bit line count would identify a particular line. Such a line count would be modulo some number large enough to allow resolution of ambiguities on a coarse basis by comparing satellite ephemeris to time of day. The 5-bit segment count would identify the precise 1500 bit data segment within each line. With these counts included in the data any particular segment could be extracted in real time from the downlink signal and processed for immediate analysis. For example, a given 20 x 40 mile area might require immediate examination because of a forest fire or other disaster. Extraction of only the data of interest would simplify subsequent processing.

6.2.6

Recorder Subsystem

The recorder subsystem represents the most uncertain area of the RCC. While it is feasible to record data rates in the 50 - 200 Mb/s range, equipment to accommodate the top end of this range is not presently available off-the-shelf. Potentially by 1973 such hardware will be readily available, probably in the form of a laser holographic recorder. However, if implementation were necessary immediately it appears that a magnetic tape system offers the minimum risk and best performance for the 199 Mb/s baseline. Should the rate increase to 200 Mb/s, this initial conclusion is probably not valid since the laser technique could be developed for essentially the same or less cost. Appendix A contains a survey of recorder technology which considers various recorder approaches and enumerates the advantages and disadvantages of each.

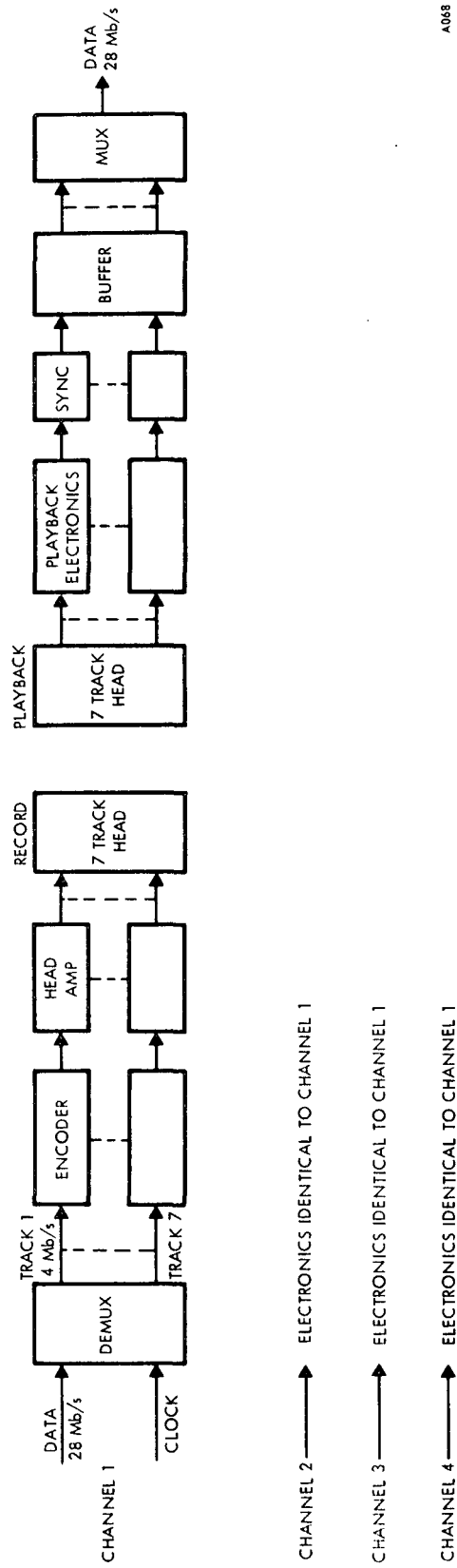
The recorder approach is illustrated in Figure 6.2.6-1. It is assumed here for the configuration given that the maximum number of channels is 4 with a maximum rate of 28 Mb/s per channel. While the maximum rate is perhaps flexible, a number of channels greater than four or a total rate much over 100 Mb/s would require an additional recorder thus increasing costs. This approach would use an existing recorder such as an Ampex FR1900 or equivalent. A spectral band would be demultiplexed into seven channels, coded, and converted to NRZ₀ data for recording on a seven track head. Upon playback each track would be NRZ₀ decoded, and remultiplexed into a nominal 25 megabit per second data stream. Additional channels could be added by adding additional heads to the recorder and additional electronics for multiplexing, coding, decoding, and demultiplexing the data. A reasonable upper limit to the number of spectral bands per recorder is four, thus requiring a total of 28 tracks.

The deskewing problem is considerably simplified by this approach since only seven tracks on the same head would have to be deskewed for each channel.

At 28 Mb/s, the packing density for 120 ips is 33.3 Kb/inch. The General Dynamics Unidar Recorder has a packing density of 33.3 K bits/inch/track which yields a bit rate of 4 Megabits per second/track at a bit error rate of 10^{-6} . Ampex has delivered the FR1900 with 32.5 Kbp/track and has achieved 50 Kbp/track in the lab at a guaranteed 10^{-5} BEP.

With the described system, we would expect to achieve a BEP of 10^{-6} and would guarantee 10^{-5} . To increase to an expectation of 10^{-7} and guarantee 10^{-6} would probably require error correction codes. These would be implemented using 512 bit IC memories and would cost approximately \$1000 per track or \$7000 per channel.

It should be pointed out that demultiplexing the input data is also required if a laser holographic recorder is utilized. Therefore, the general system which has been outlined could replace the magnetic recorder with an optical recorder in



A068

Figure 6.2.6-1. Recorder Subsystem Utilizing a Magnetic Recorder

concept. Individual channels would then be available for analysis. The laser approach should allow reconstruction of the original bit stream if required since the inherent timing and skewing problems encountered with tape are avoided. With continuing development of optical techniques, an appropriate holographic recorder will probably be available in 1975, or before.

With the magnetic recorder approach, a standard 16 inch reel of tape provides approximately 15 minutes of record time at a standard 120 ips rate. Thus, each satellite pass would require 1 reel of tape and with up to three passes per day on the order of 1000 reels of tape per year are consumed. According to Ampex, the latest GSA price for certified 1 inch wideband tape is \$99.30/7200 ft. reel and \$120.67/9200 ft reel in small quantities. Quantity discounts are available. Still, the yearly cost of consumables is considerable. (While precise estimation of film costs used with alternate recording techniques is difficult, all indications are that the consumable cost is comparable to that of magnetic tape.)

6.3 Cost Estimates

The basic cost of the RCC which has been described is estimated in this section. The figures presented are realistic since vendor quotes have been obtained for many items. In the less well defined areas, every attempt has been made to be accurate and to point out potential variations.

The basic assumptions are:

- a. 1971 dollars are assumed.
- b. Development costs are included for items not presently off-the-shelf. In many cases such costs will not be encountered in the time frame of interest.
- c. Basic costs are for the 15.25 GHz, 100 Mb/s system. Variations are noted.
- d. It is assumed that a suitable site with facilities is GFE.
- e. Documentation consistent with that on current NASA programs is assumed.
- f. No profit is included in the estimates.
- g. Conus installation is assumed with shipments via government Bill of Lading.
- h. A system with little technical risk is priced.

The corresponding system costs are tabulated in Table 6.3-1 for both the first system and on a recurring basis. Potentially, on the order of \$400K (or any lesser amount) could be saved from the cost of the first system should appropriate development occur prior to its fabrication.

Table 6.3-1. RCC Estimated Cost for Baseline 15.25 GHz, 100 Mb/s System

	First System Cost	Recurring Cost
Antenna Feed and Microwave	65K	35K
Antenna Pedestal and Reflector	150	100
Antenna Control	220	135
Receiver	195	160
Data Processing ¹	175	50
Data Recording	200	150
Documentation	240	-
Other ²	355	220
	<hr/>	<hr/>
TOTAL	\$1,600K	\$850K

¹ Assumes PSK; Cost increases by approximately 35K for QPSK.

² Includes Program Management, System Engineering, Integration, Installation, Test, etc.

The item most likely to escalate in price is in the documentation area while a similar reduction is possible in the receiver area. If a sensitivity analysis is performed and the cost of each element varied by a factor of two in each direction the nominal percentage changes in total cost are approximately -7% and +12.5%. However, while variations in the element costs presented are to be expected, the net effect should be small compared to the tabulated figures.

The major impact of a change in bit rate would be the recorder subsystem for which a 200 Mb/s system would effectively double the recorder costs. On a RF basis the change is easily accommodated by utilization of a cooled parametric amplifier at an increase in cost of approximately 25K. However, operation and maintenance costs are increased. The other system element impacted is the data processing equipment. A 200 Mb/s system should utilize QPSK to conserve bandwidth and would therefore require two BSSC's and decommutators. The net effect therefore of a 200 Mb/s system is a cost increase of approximately \$275K for the first system and \$200K for subsequent systems.

Conversely, a reduction in data rate to 50 Mb/s provides a savings of approximately 100K. At this lower rate several recorder approaches are available and have been proven. Additional savings could be achieved by designing a minimal system.

One of the important considerations is the impact of a carrier frequency other than 15.25 GHz. The cost impact is summarized in Table 6.3-2 for the alternate frequencies of 8.5 and 21.2 GHz. The differentials from the 15.25 GHz system are less than initially expected. However, two points should be emphasized. First, as explained in Section 4.1, a realistic 21.2 GHz system incurs a substantial performance penalty and second, implementation at 21.2 GHz will almost certainly require expenditure of full RF development costs (including satellite equipment). It is unlikely that another program will be implemented in that frequency band in the time frame of interest. Generally speaking, less risk is present at the lower frequencies. Even though less cost difference than might be anticipated is indicated, implementation at 21.2 GHz is not the most desirable alternative. However, it is feasible to provide adequate performance for the nominal price increase.

Table 6.3-2. Cost Impact of Alternate Center Frequencies

Subsystem	8.5 GHz	21.2 GHz
Structure	-30K	60K
Feed	-15K	25K
Receiver	-20K	100K
Other	<u>-10K</u>	<u>25K</u>
Total	\$-75K	+\$210K

7.0 LOCAL USER TERMINAL (LUT) CONFIGURATION

This section describes the basic characteristics, performance, and estimated cost of the range of alternatives for the LUT which have evolved during this study effort. It is seen that a cost effective terminal can be provided to local users which will allow direct reception and hard copy production of high resolution image data from the spacecraft.

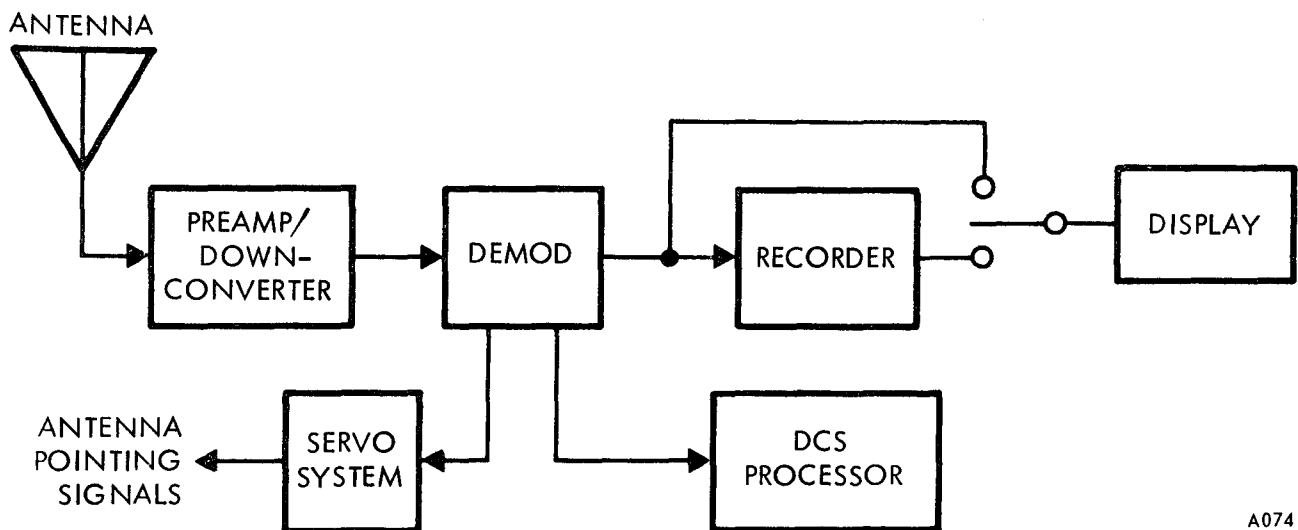
7.1 LUT General Characteristics

The purpose of the LUT is to receive, demodulate, and display image data transmitted from the subject spacecraft. It is also desirable to provide a recording capability which allows the display subsystem to operate off-line. Since a limited geographical area is of interest to the local user, the system design is affected. However, as has been discussed in Section 4.2, the spacecraft antenna is the primary system element affected by this consideration. Ground antenna elevation angle could be constrained to a minimum of 20° or so but the ready availability of more flexible structures precludes the potential advantage of this. Important factors for the LUT are simplicity and reliability. These are achievable via maximum utilization of standard, maintainable equipments. The system described herein meets the requirements and provides a high quality, well engineered approach consistent with standard NASA practices. Alternatives, using surplus equipment for example, are also discussed.

A general block diagram of the LUT which illustrates the functional elements required to meet the stated requirements is given in Figure 7.1-1. The basic subsystems can be grouped into major equipment categories of:

- 1) Antenna and Structure Subsystem
- 2) Servo Subsystem
- 3) Receiver Subsystem
- 4) Recorder Subsystem
- 5) Display Subsystem

Additionally, the terminal equipments might contain a data processing subsystem (probably in the form of a mini-computer with appropriate I/O) and equipment for receiving and processing DCS type data. These alternatives are discussed along with each of the basic elements in Sections 7.2 and 7.3 which consider performance and cost respectively.



A074

Figure 7.1-1. Functional Block Diagram for Local User Terminal

A range of alternatives have been considered for the LUT. The basic features and parameters of the terminal options are summarized in Table 7.1-1. The alternatives are characterized by antenna size for the "S-Band" system utilizing parabolic reflectors or by frequency for the VHF/UHF system. As discussed in Section 4.2, the S-Band results are frequency independent over a wide range so the parameters presented are generally applicable. It has been determined that a receiving terminal at S-Band utilizing a parabolic reflector with diameter ranging from 3 to 10 feet along with a solid state receiver front end (and standard telemetry receiver) provides performance consistent with local user requirements. Equivalent performance, with resolution on the order of 150 meters/line-pair, can be realized at VHF with an inexpensive, manual track antenna and similar receiver subsystem. Analog FM is recommended as the modulation technique because of performance and complexity factors. However, digital transmission is also possible and Table 7.1-1 includes alternatives based upon digital PSK with and without coding. The signal quality utilized as a baseline for the results presented is a 10^{-5} BEP for digital transmission and a video signal-to-noise ratio of 30 dB for analog signals. The assumptions upon which the resolution factors are computed are discussed in detail in Section A.1 of Appendix A.

Table 7.1-1. Summary of Local Terminal Alternatives

System Alternative Parameter	10' Dish	10' Dish w/Coding	6' Dish	6' Dish w/Coding	3' Dish	VHF/UHF
Carrier Frequency	S-Band	S-Band	S-Band	S-Band	S-Band	350 MHz
Bit Rate (Mb/s for PSK)	1.18	3.72	.43	1.36	.11	1.1
Video Bandwidth (kHz for Analog FM)	275	—	100	—	25.6	250
*Resolution (m/line-pair)						
Digital Transmission	205	110	340	190	675	210
Analog Transmission	140	—	250	—	485	155
Terminal Cost (\$K)	198	228	178	218	80	121

*100 mile swath width

7.2 LUT Subsystems

The basic elements of the LUT which have been identified are discussed in this section. Most of the system elements required are currently available as off-the-shelf equipments.

7.2.1 Antenna and Structure Subsystem

Utilization of standard antenna and antenna mounts is envisioned for the LUT. Several vendors have been surveyed and can provide suitable structure, reflector, and feed elements. Elevation over Azimuth type mounts are most common of those presently available. However, X-Y mounts do have dynamic advantages and Radiation has recently developed a line of economical X-Y type structures which could be used for the given application. Minimal dynamics ($\dot{\theta} \sim 1^\circ/\text{sec}$, $\ddot{\theta} \sim .1^\circ/\text{sec}^2$) must be provided consistent with near overhead tracking of a 500 nm satellite.

As a consequence of the desire to minimize costs, a conical scan type feed/tracking system is recommended for those systems requiring autotrack capability. Considerations for manual or program tracking have been included in the study and are discussed in Section 7.2.2. It has been found that the basic cost break point is encountered when a manual track system becomes feasible (as opposed to changes in dish size) as for the smaller S-Band dishes or the VHF/UHF system which requires only 18 dB of antenna gain. This gain can be provided at these frequencies with off-the-shelf, inexpensive, manual tracking antennas. One suitable unit is a quad helical array such as Andrews type No. 52650 which provides 19 dB gain. Simple helical antennas can provide nominally 13 dB gain in the frequency band of interest.

In the course of this study effort, a system which would track in one axis only has been investigated and found to be minimally feasible for a 10' antenna system at S-Band and the 500Nm polar type orbit. However, extensive pre-pass alignment is required in the other dimensions and some form of closed loop control system is still desirable. With these considerations there is no apparent cost advantage in the single axis track system and performance is actually degraded due to increased tracking error. Consequently, this approach is not recommended at this time. It is possible that more detailed study or future development might provide such a cost effective approach. Therefore, the concept should not be dismissed.

Suitable vendors for the basic antenna system include Scientific Atlanta, Andrews, and ABA Industries. Other vendors supply similar equipment.

7.2.2 Servo Subsystem

Antenna control must be provided since directional antennas will be utilized. Table 7.2.2-1 gives nominal 3 dB beamwidths for the various alternatives and thus provides insight into the tracking problem. The VHF system and 3' antenna at S-Band have relatively broad beamwidths and consequently a manual tracking system is adequate to position the antenna on the basis of received signal strength. The dividing line between requirements for an autotrack system versus manual track is somewhat arbitrary.

Table 7.2.2-1. Antenna Beamwidths for the LUT

Antenna	Beamwidth (3 dB)
10' dish*	3.2°
6' dish*	5.5°
3' dish*	11°
VHF/UHF (18 dB gain)	20°

(*frequency of 2.2 GHz assumed)

For the purpose of this discussion it is assumed that the 6' and 10' diameter dish systems must have auto (or program) track capability. That is, the antenna positioning is other than manual control.

A conical scan system which tracks on the basis of received signal strength will provide acceptable performance in a cost effective manner. The closed loop system for autotracking is straightforward and is a good field proven technique.

Given that autotrack is required, little cost differential is seen with changes in antenna size over the range of interest.

Program track is a feasible approach and can be provided to supplement the basic autotracking system or as a total alternative. However, increased complexity and cost is inherent because of the computer, I/O devices, programming and documentation, etc. It appears that the cost effective conical scan system is the most appropriate for this application. However, if a computer is included in the system for data processing, program tracking is more desirable and should be utilized. Under this condition, a program track mode is provided at minimal additional cost.

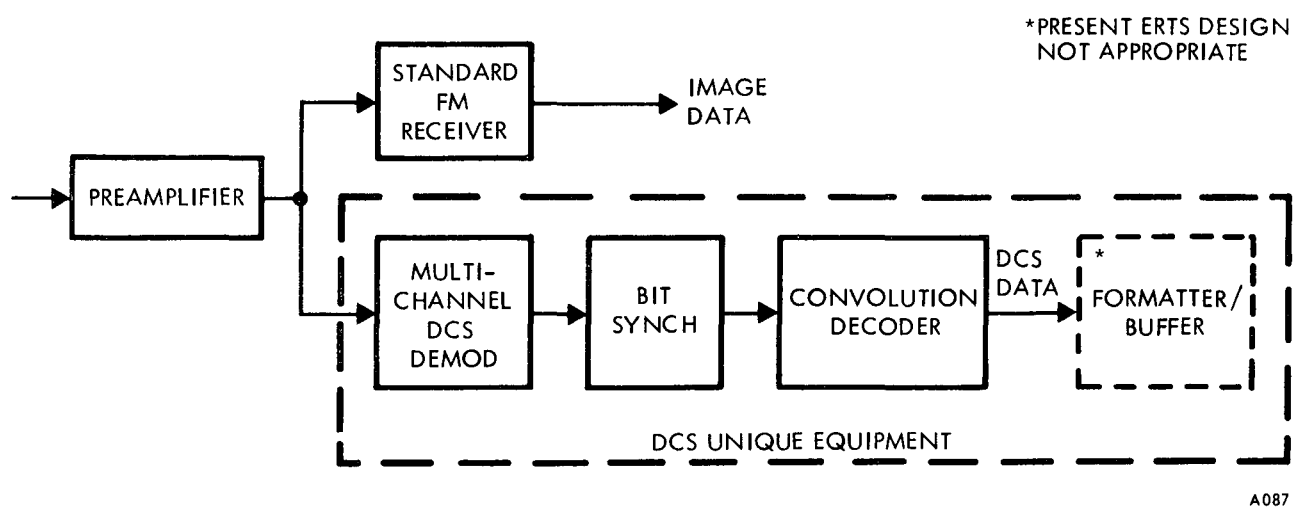


Figure 7.2.3-1. LUT Receiver Subsystem for DCS Capability

7.2.3 Receiver Subsystem

The receiver requirement for either the S-Band or VHF/UHF system is easily satisfied with standard telemetry receivers such as those available from Microdyne (for an analog FM system). This receiver line includes a range of compatible heads which provide the desired carrier frequency flexibility. A preamplifier, such as available from Avantek or Watkins-Johnson, is required to satisfy the noise figure and performance requirements specified in Section 4.2 when operating at S-Band, thus increasing the costs slightly. Bandwidth requirements are indicated in the summary of Table 7.1-1. RF bandwidth is of course dependent upon modulation index. Band spreading factors on the order of 5-10 have been found to be appropriate as spectral occupancy is against modulation gain.

Should digital modulation be utilized, the complexity of the receiver subsystem would be increased. Computations have assumed PSK and a standard line of PSK demodulators is not currently available though there is no technical risk involved. Obviously, a standard FM receiver with discriminator could be utilized with appropriate transmitter if the degraded performance of noncoherent FSK versus PSK could be tolerated. For example, noncoherent FSK requires approximately 4 dB greater predetection signal-to-noise ratio than does coherent PSK at 10^{-5} BEP. All other factors remaining constant, the allowable bit rate is reduced by a factor of around 2.5 for FSK in this situation.

A potentially desirable feature for the LUT is a DCS type capability. Such capability can be provided with a configuration illustrated in Figure 7.2.3-1 which is consistent with the individual carrier approach described in Section 4.2. The DCS, as configured for ERTS A&B, requires fairly complex demodulation and processing equipment. Since this basic configuration is assumed here, the same equipment is required at the LUT. Specifically, a multi-channel FM demodulator, control logic, a convolutional decoder, and formatter-buffer are required. Since addition of this equipment results in a very significant percentage cost increase for the LUT, alternative implementations should be considered. Means of reducing the LUT complexity via additional burden on the satellite are appropriate areas of analysis.

7.2.4 Recorder Subsystem

A recording capability can be provided for the LUT with standard medium bandwidth recorders such as Ampex Models PR-500 or FR-1300. These units have bandwidths of 150 kHz and 300 kHz respectively and provide a minimum of 12 minutes recording time which is quite adequate the pass durations expected. Signal-to-noise ratios of 34 to 35 dB can be achieved with appropriate filtering in the wideband direct modes.

The recorder provides the desirable features for the LUT of:

- 1) Permanent or temporary data storage for off-line processing.
- 2) Capability for interfacing reduced bandwidth signals with the display subsystem by reproducing at reduced tape speeds.
- 3) Data storage in event of display system failure.

Because of these factors and the fact that an appropriate recorder is relatively inexpensive, it seems that this capability should be included in the LUT.

If the system is to be implemented digitally, the recorder is still desirable but complexity is increased. Equivalent digital data rates are on the order of 1-3 Mb/s. Therefore, either a wideband recorder such as FR-1900 or FR-2000 must be used or special record-reproduce electronics provided with the medium bandwidth units. Utilization of the medium bandwidth units requires recording of the serial bit stream via demultiplexing over multiple tracks.

7.2.5 Display Subsystem

The type of display to be selected for the LUT will come from a wide range of possibilities: continuous strip versus single frame processor, manual or automatic processing, real time or off-line operation, CRT or laser scanner, etc. Many of the considerations relative to the display system are presented in Section A.1 of Appendix A. Based upon that discussion, it appears that a continuous strip CRT type scanner with manual film processing is appropriate. However, there are many factors which must be considered in making this choice which do not lend themselves to a general answer.

In any eventuality some desirable features of the display system can be discerned. A minimum of 16 grey levels resolving power should be available. (This may be one parameter which can vary from user to user dependent upon the specific requirements.) A frame width of 7.3 inches produces a scale of 1: 1,000,000 assuming an earth swath width of 100 nm. This width leaves ample space in the margin for annotation describing the sensor source or providing ground registration information. It has been assumed in the LUT description that such annotation data is inserted on the spacecraft. Any ground signal processing will require equipment not identified in the terminal description given here.

Other display parameters of interest are summarized in Table 7.2.5-1 for the appropriate range of data rates. Reference is made to Appendix A for the assumptions upon which the various relationships are based.

Table 7.2.5-1. Display Parameter Values

	Case 1	Case 2	Case 3	Case 4	Units
Bit Rate*	10^5	10^6	4×10^6	10^7	Bits Per Second
# Elements/TV-Line	760	2400	4800	7600	Elements/TV-Line
Scan Rate	29.7	93.5	187.0	297	TV-Lines/Second
# TV-Lines/Inch	104	329	658	1040	TV-Lines/Inch
TV-Spot Diameter	9.60	3.04	1.52	0.96	Mils/Element
Resolving Power	36.8	116	232	368	Optical Line-Pairs/Inch

*Divide by factor of 8 to convert to equivalent video bandwidth.

7.3 Cost Estimates

Cost estimates are presented in this section for the variety of LUT alternatives which have been presented. As with any cost estimate, the underlying assumptions and conditions must be made clear if the resultant figures are to have any meaning. The costs are given for 1971 dollar values, that is, assuming no inflation. Cost of facilities is not included in the basic terminal price. Appropriate building and grounds, access, etc., are assumed available. CONUS installation is assumed. The figures given here assume a well engineered system consistent with standard NASA procurements and also that a medium number of terminals are to be purchased. Profit is not included in the estimates. Individual users with appropriate knowledge (for example, a university) could assemble a workable system using surplus equipment for substantially less cost than given here.

It is seen that a major cost breakpoint is encountered when the antenna beamwidth becomes broad enough to be consistent with a manual positioning system. Otherwise, the area where the greatest cost variation might be expected is the display subsystem. The display cost can potentially range from a small percentage to greater than 50% of the total system cost.

Table 7.3-1 summarizes the cost estimates for the basic LUT. This system utilizes analog FM and makes maximum utilization of available equipment.

Table 7.3-1. Basic LUT Cost Estimate

Subsystem	10' Dish (S-Band)	6' Dish (S-Band)	3' Dish (S-Band)	VHF/UHF System
Antenna and Structure	30	30	10	10
Servo	40	30	—	—
Receiver	10	10	8	8
Recorder	8	8	7	8
Display	60	50	30	60
Integration, Installation and Test	30	30	15	15
Other*	<u>20</u>	<u>20</u>	<u>10</u>	<u>20</u>
Total (\$)	198 K	178 K	80 K	121 K

*System Engineering, Program Management, Documentation, etc.

Several options to Table 7.3-1 are possible and are discussed individually below. First, an autotracking system utilizing conical scan techniques has been assumed. A program track system can also be implemented, but the estimated cost differential is \$30,000. However, should it be desirable to include a mini-computer with appropriate I/O devices in the terminal anyway, for minimal signal processing as an example, program track becomes more desirable and can be provided with little cost differential on a recurring basis.

A digital implementation will increase the system costs significantly. Considering the PSK demodulator, convolutional decoder to provide improved performance, and increased recording complexity an increase on the order of \$30,000 is encountered. Still digital implementation is potentially more compatible with the spacecraft hardware so it cannot be totally dismissed.

If only one system is purchased, or if the first system cost burden is not amortized, a significant differential is to be expected. The first system could be expected to cost an additional \$120,000 for the 10 and 6 foot systems and approximately \$40,000 for the other two options.

Addition of DCS capability to the LUT, if the present DCS design is utilized, significantly increases the estimated cost. The Receiving Site Equipment (RSE) designed and fabricated for ERTS A&B DCS costs approximately \$100,000 on a recurring basis. While all of the RSE is not required for the LUT application, the major portion is required. Specifically, the LUT would not require the Formatter/Buffer which reformats the data into standard NASCOM format. Because of the large percentage cost, alternate DCS implementations should be investigated.

It was earlier indicated that the display system cost could be expected to be subject to wide variations dependent upon the specific capabilities provided. Tables 7.3-2 and 7.3-3 illustrate such potential variations for various alternatives for the reproducer and film processor.

Table 7.3-2. Reproducer Cost Variations

Scanner Reproducer	Estimated Cost 1000 - 4000 Elements/Line	Estimated Cost 5000 - 7000 Elements/Line
Real Time Continuous		
CRT Line Scanner	15 - 30 K	30 - 50 K
Laser Line Scanner	30 - 70 K	70 - 120 K
Non-Real Time Single Frame		
CRT Line Scanner	15 - 30 K	30 - 50 K
Laser Drum Scanner	12 - 25 K	20 - 40 K

Table 7.3-3. Film Processor Cost Variations

Film Processor	Estimated Cost
Continuous Strip	
Automatic	25 - 50 K
Manual	6 - 18 K
Single Frame (Drum Type)	
Automatic	5 - 30 K
Manual	1 - 5 K

To summarize, some of the more salient conclusions, observations and recommendations which have been stated in this report, both explicitly and implicitly, are repeated in this section. The objective of optimizing the system configuration to meet the needs of two distinct user types is very desirable in order to maximize the utility of future operational earth observation systems. It appears that this objective is better satisfied by a system employing two independent transmission elements each tailored for the respective user type. This is as contrasted to a single transmitter approach wherein each user would be forced to receive all transmitted data. The alternative to reception of all data, for the single transmitter system, is an inefficient modulation/multiplexing approach which appears to penalize all users in this application.

The first user type requires reception and recording of high rate, multi-spectral band image data. It has been shown in this study that the required capability for data rates to 200 Mb/s can be achieved in a cost effective manner with low technical risk. Digital transmission with PSK modulation is a good modulation technique. Quadri-phase (QPSK) should be utilized if bandwidth occupancy is a major concern (as it probably will be). QPSK has an additional advantage of providing independent channels which could utilize different timing. Because of the extreme data rates and relative ease with which the link can be closed, utilization of channel encoding does not appear to be attractive based upon link considerations. However, error correction encoding will probably be a necessity to ensure 10^{-6} BEP in the recording process and it would seem desirable to perform this encoding on the spacecraft. The recorder is probably the most critical subsystem in the ground station with present technology. However, development is progressing and it is no doubt feasible to record high rate data to rates beyond the 200 Mb/s of interest here. Holographic laser techniques seem to be the most promising. While the baseline system has assumed operation at 15.25 GHz, the alternate frequencies of 8.5 and 21.2 GHz have been considered. The lower frequency is attractive due to reduced losses and greater component availability. Utilization of 21.2 GHz does not result in as great a cost differential as might be expected, but performance is degraded and more risk is to be expected.

The second user type requires less data but has a need for display capability. It has been determined that medium resolution (around 100 - 200 meters) image data can be provided to such a user with a terminal and associated display system at reasonable cost. While the study effort has emphasized operation in the S-Band region, the same capability can be achieved with frequencies in the 100 - 500 MHz region with significant cost savings. Consequently, the potential for an approved allocation in this region should be investigated. Analog FM, because of relative simplicity to the user and good performance is the favored modulation technique. Equivalent capability can be achieved with digital transmission and convolutional encoding. However, user cost is increased. A DCS capability can be designed into

the system with little perturbation on the image channel capacity. The DCS, as configured for ERTS-A, requires complex and costly (on a relative basis) ground terminal equipment. Accordingly, alternate implementations require investigation for the purpose of reducing user cost since the application envisioned here will serve a large number of users.

Several areas worthy of additional consideration have become apparent during this study effort. In order to further definitize the system configuration, specific user requirements must be considered. Several "data content" systems should be configured using the results of this study and general user requirements. These alternatives could be utilized to provide a shopping list for potential users and the results of a subsequent survey should be a major factor in defining the ultimate system. Of course, an equally important factor will be experimental results obtained with ERTS-A&B.

A second system level consideration relates to the existing NASA tracking and data acquisition network. The feasibility of modifying these facilities to meet both the RCC and LUT requirements should be investigated. The cost of such modifications, when compared to the options outlined in this report, would indicate the best approach since most user needs could probably be satisfied with existing site locations if appropriate equipments were available.

Further study of high rate recorder technology is indicated. A survey of present and expected technology for digital recorders for 100 - 200 Mb/s rates would identify the most promising candidates and spotlight any development which might be necessary. One factor which should be emphasized in such a study is ease of data retrieval both partially and in total. Partial retrieval allows rapid dissemination of the desired data to various users. Ease of playback in total allows an inexpensive reproducer at the processing center.

A facsimile type distribution should be considered as a method for disseminating data in general, and specifically as an alternate approach to satisfying needs of local users. The ground based system would extract the desired data from the total received at the RCC and transmit it to the users, probably via standard phone lines. This approach would supplement (or circumvent the need for) the local terminals described in this report.

Two other areas having major impact on the local user concept have been identified as requiring further consideration. First, effort should be made to obtain a clear channel in the 100 - 500 MHz frequency range for this application. This allows a very cost effective LUT. Second, alternate DCS implementations tailored to a multi-user system should be considered. These DCS alternatives would provide decreased complexity at the ground receiving terminal at the expense of increased spacecraft complexity.

Other study and analysis will be necessary as system definition progresses. An excellent example of this is the spacecraft antenna/ground sensitivity trade-off for the high data rate RCC link. While the high gain satellite antenna appears to be an excellent approach at present, further refinement of the analysis will be possible as the spacecraft configuration evolves. Another example is the optimum signal format and desirable on-board processing which requires more precise sensor definition.

Several of the key system elements should be breadboarded to facilitate development. On-board processing elements, especially those related to the direct transmission system for local users, should be interfaced with the high data rate multiplexing breadboards. Spacecraft RF equipment requires development, especially should implementation at 21.2 GHz be required. Likewise, ground system elements may require development and this factor should be kept under consideration. The recorder survey recommended above will identify any breadboard activity required in that area.

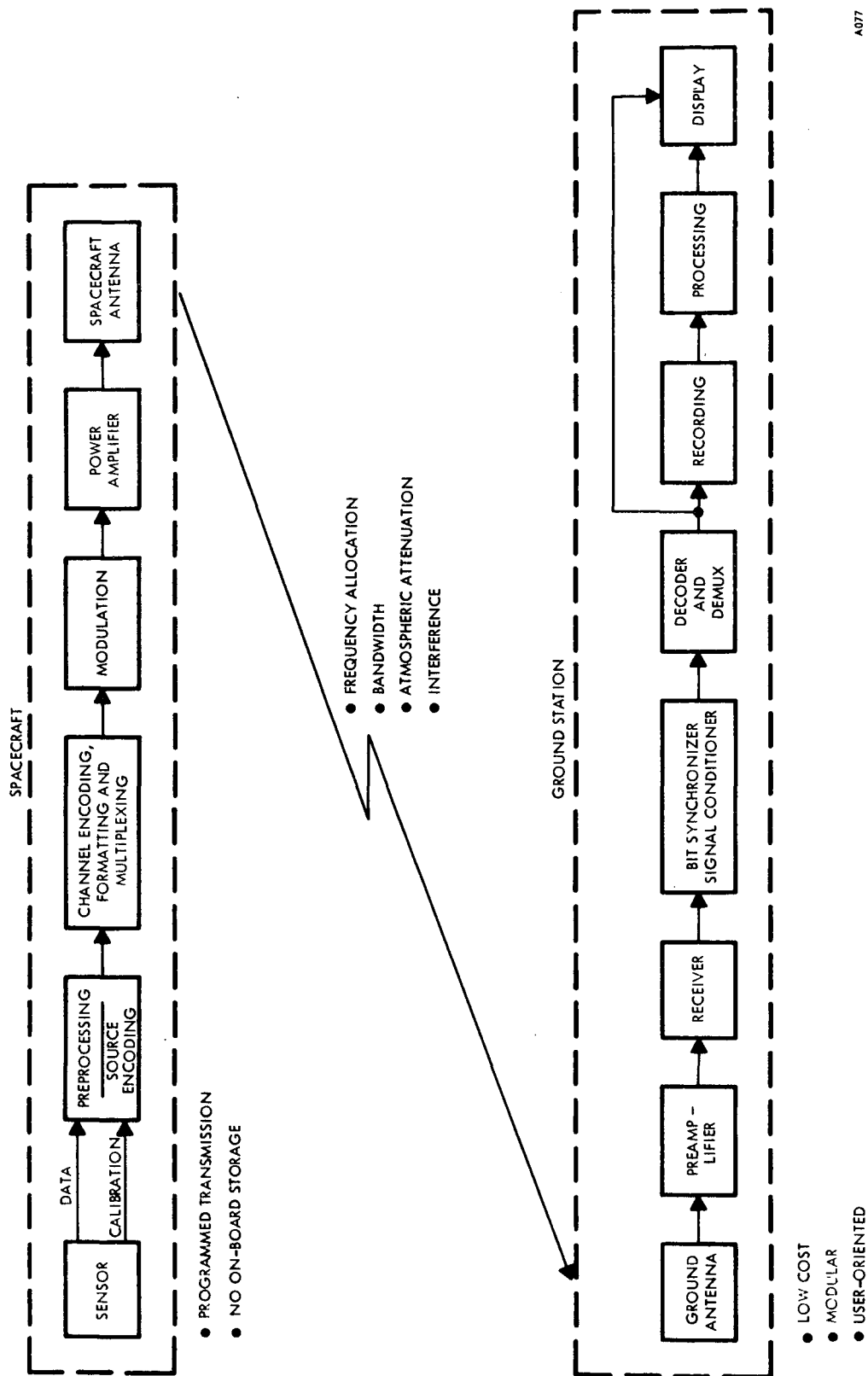
The total system could be breadboarded and experimented results utilized to verify performance. However, a more desirable alternative is to breadboard the key elements indicated and to verify performance via simulations. It is possible to perform accurate simulations of all subsystems, including the scanner, RF link, baseband, and display system. Such simulations allow for trade-offs not amenable to analytical evaluation to be performed and optimum system specifications to be generated.

APPENDIX A

SPECIAL TECHNOLOGY AREAS

This study has been concerned with a diverse range of technology areas. Many interesting and important subjects have been treated superficially, truncated prematurely, or left out altogether in the text of this report. Fortunately, a few were left over for inclusion. The material presented in this appendix is intended to supplement the previous information. This is done by considering in more depth a number of topics which directly affect the system analyses which has been performed.

Figure A-1 is a functional block diagram which indicates and summarizes the technology areas applicable to this study effort. In this appendix, the display systems, modulation and coding, and information storage topics are explicitly discussed. Other areas are implicitly included.



A077

Figure A-1. System Block Diagram

A.1

IMAGING SYSTEMS AND DISPLAY TECHNOLOGY

The following pages discuss some of the major system level relationships and parameters that must be considered in selecting, designing, or evaluating the display segment of an optical mapping or reconnaissance system. For the sake of discussion, it is assumed that the display output required is a photographic negative of a 100 nautical mile square of the earth's surface. The display input is assumed to be an electrical signal generated by an optical scanner mounted in a nominal 500 nautical mile circular orbit satellite similar to that employed by the ERTS system.

The mission of any optical mapping system is to provide photographs of a portion of the earth surface. How well a given system performs that mission is generally measured in terms of three parameters:

1. Picture Quality

Picture quality includes many sub-parameters such as the level of detail that can be distinguished (ground resolution); how accurately the photographic image represents the object shape, size, and location (distortion); the smallest increments of contrast change that can be detected (grey level resolution); the range of contrast levels than can be accommodated (dynamic range); and the noise content of the image.

2. Picture Quantity

Picture quantity is the size of the earth area photographed. To be meaningful, this parameter must be considered on the basis of object area per frame as well as object area photographed per unit time.

3. Timeliness

This parameter is a measure of the system response time to a command to photograph a given region. It may include only the transfer and display time for a particular image, but it may also include the time lag between the command decision and the actual collection of image data by the satellite optics. That is, it may be a function of the satellite orbit, the number of satellites supporting the system, and the satellite orbit position relative to the target area when the command was received.

The fundamental functions (from a display viewpoint) that must be performed by an optical mapping system are illustrated by the block diagram of Figure A.1-1. The optical scanner collects image information from the object of interest and provides an optical waveform, either in the space domain or the time domain, to a device that converts optical amplitude changes to variations in electrical amplitude. The electrical/time waveforms are processed to achieve the proper form for modulation of a communication channel, time synchronized and tagged according to some space-to-time mapping algorithm, and combined with any additional system information needed by the display to provide the desired photographic negative. Depending upon the availability and capacity of the communication channel, the processed waveform will be either transmitted in real time or stored for transmission at a later time at a rate that may or may not be the same as the collection rate. The display segment performs the inverse of the operations accomplished in the satellite. The received image data is separated, processed, and converted from an electrical time domain waveform to an optical space domain waveform. The final step is to transfer the data from an image plane within the display to film and the development of a photographic negative.

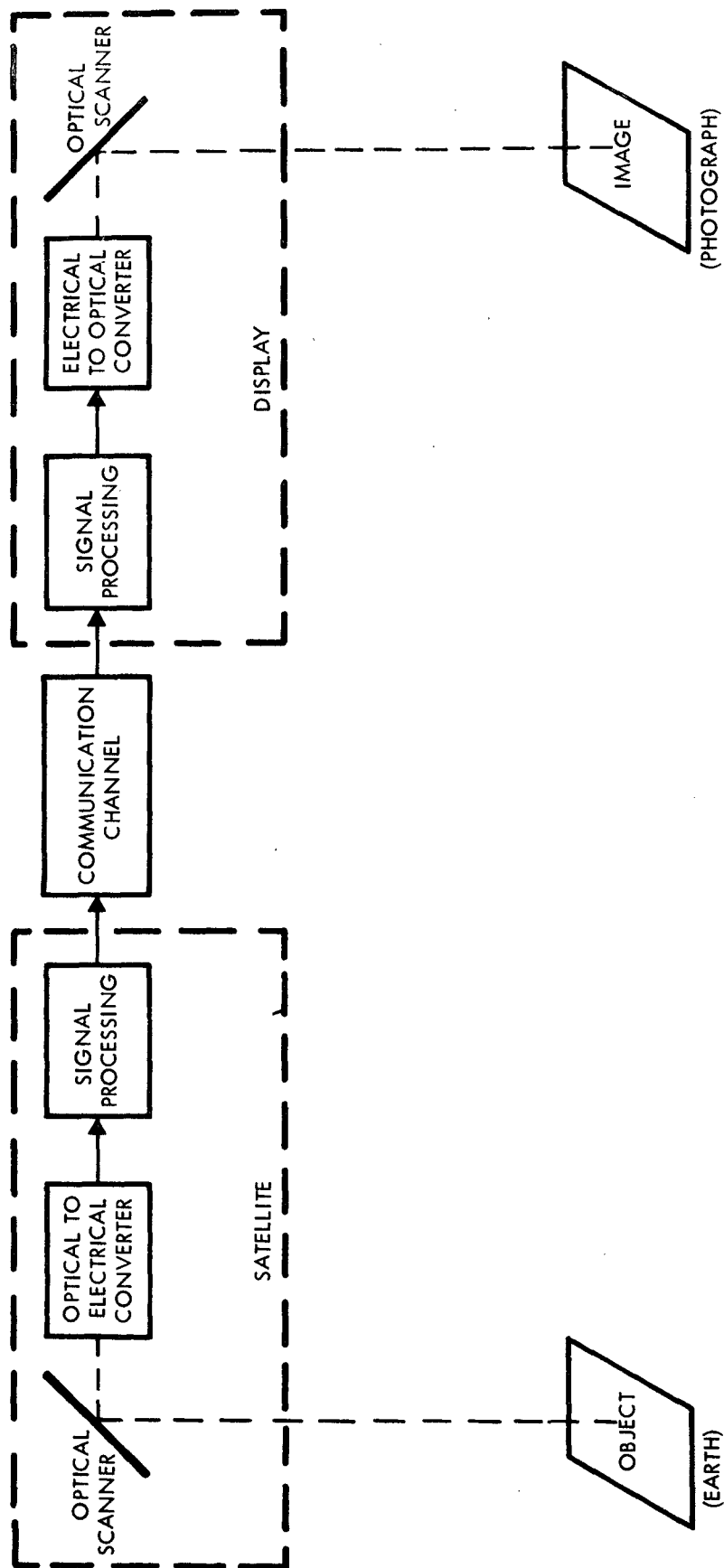
A.1.1 Object Scan Techniques

The various techniques for scanning a given area apply equally to the object scan requirements of the satellite and the image scan problem of the display. As such, the details of individual methods for scan generation will be discussed later under the section concerned with Display Techniques. It is instructive however, to divide object scan techniques into two general classes and investigate the impact of each upon system performance.

A.1.1.1 Direct Object Scan

The conversion of optical signals in the space domain to optical or electrical signals in the time domain requires some form of raster scan. One common approach to generating a raster is to scan the object directly with a large aperture (small optical beamwidth). This technique typically uses the spacecraft motion to provide the along-track raster dimension. This method allows the pointing vector of the optics to remain normal to the spacecraft roll axis such that each cross-track scan is a segment of an earth great circle that contains the satellite sub-point.

As the optical pointing vector is scanned off nadir, the cross-track distance on the earth surface that is contained within a given differential optical angle increases because the pointing vector is no longer normal to the surface of the earth. Depending on the maximum angle scanned, this can result in significant distortion of both size and location at the outer edges of the scan. Since along-track scanning results from motion of the satellite, this distortion does not occur in



A067

Figure A.1-1. Optical Mapping System Functional Block Diagram

the along-track dimension of the raster. If this distortion component is to be corrected by signal processing, the fact that it occurs in only one dimension greatly simplifies the correction problem.

A.1.1.2 Indirect Object Scan

The second method of generating a raster is to instantaneously expose on entire image plane capable of storing the object information and then scanning the image plane. The most common storage techniques suitable for the image plane are the CRT vidicon tube, photo diode matrices, and direct film exposure. Because exposure of the image plane is virtually instantaneous, optical distortion that occurred only in the cross-track dimension for the direct scanning method will appear in both dimensions of the raster for indirect scanning. Thus, if it is desired that the display correct this distortion source, a given data sample display point within the raster must be moved in both dimensions. This correction is considerably more difficult to implement than is the single dimension correction.

A.1.1.3 Projections

Although the data from either scan approach can be corrected for display on any projection desired, the form of the data received from a direct scan system is probably displayed more easily as a transverse cylindrical (mercator) projection where the symmetry of the indirect scan appears to be more aligned toward a plane projection. As the area of an earth frame becomes small, the assumption of a flat earth allows the uncorrected data to be displayed on a plane projection with very little distortion. Obviously, the frame size at which this is true depends upon the amount of distortion that a user is willing to tolerate.

A.1.2 Display Techniques

The input to the Display Segment shown in Figure A.1-1 is an electrical/time waveform similar to that found at the output of the signal processing function in the satellite. The display must convert that waveform to an optical waveform in the space domain and then print the optical/space waveform as a photographic negative. The electrical-to-optical conversion is typically accomplished by using the electrical signal to modulate the excitation of an optical source. The time domain-to-space domain conversion is achieved by scanning a raster with either the excitation or the optical source.

A.1.2.1 Reproducer Scan Techniques

All of the reproduction scan techniques discussed utilize line scan devices. That is, the raster is generated by scanning a complete horizontal line, then another displaced vertically from the first, and so on until an entire image plane has been scanned.

Drum Type Scanner

In a typical drum type scanning mechanism the film is placed on a drum within a light-tight enclosure. The drive motor rotates the drum while the modulated light source reproduces each line on the film.

The light source advances along the axis of the drum so each rotation of the drum produces a new scan line. The drum technique lends itself to obtaining high-quality uniform copy at relatively low cost. In addition, it is relatively easy to maintain close tolerances between the drum and optics, and drive mechanisms are moderately easy to implement and control. On the other hand, the drum technique is more difficult to automate because the drum must be stopped and the film mechanically loaded and unloaded; a significant problem if many successive negatives are to be scanned in real time.

Rotating Mirror Flat Bed Scanner

With the rotating mirror flat bed scanner a modulated light source is deflected along the scan line by a multisided rotating mirror. The film advances after each scan line so each line of the picture is painted in succession. The advantage of this type of flat bed scanning is that a large supply of film can be stored in a cassette and that variable-length pictures are readily obtainable with this approach. The technique has a disadvantage in that the scan is nonlinear and the focal length is not uniform across the entire length of the scan. Correcting techniques must be applied optically or electronically to minimize these problems.

Rotating Mirror Curved Film Plane Scanners

The curved bed scanner was developed to eliminate the nonlinearity found in the flat bed scanner. The film media is placed in the curved tray and the scanning takes place as described for the flat bed scanner with the modulated light source being deflected by the rotating mirror. The curved film tray does, however, complicate automatic loading and unloading of the film.

CRT Line Scan Reproducer

This technique is one of the methods which employs a CRT. Each scan line is reproduced on the face of the CRT, with the optics projecting this image onto the surface of the film. After each line is scanned, the film advances to allow the next line to be reproduced in sequence. This technique has the features of cassette loading and variable-length copy. It has the disadvantage of limited resolution, particularly where a long scan line is involved. A nonlinear scan results as in the flat bed scanner, however, the inertia free electrostatic or electromagnetic deflection circuits of the CRT make linearity correction relatively simple.

CRT Raster Scan Reproducer

The CRT raster scan technique is similar to that employed in the CRT line scan reproducer. The difference is that this approach uses vertical deflection in the CRT instead of film movement to generate the vertical raster dimension.

The lens projects the CRT image onto the surface of the film, and the film is exposed as the electron beam scans a complete raster on the face of the CRT. This technique has the advantage of extremely simplified mechanical film handling requirements. Since the film is stationary during the complete reproduction cycle, precision advancement of the film on a line-by-line basis is not required. The technique is limited in resolution capability in both the scan and the line advance direction due to the limited resolution capability of the CRT.

Fiber Optics Line Scan Reproducer

In a typical fiber optic line scanning technique, the imaging end of the fiber optic bundle has the fiber optics aligned in a straight line. The transmit end of the fiber optic bundle is formed in a semicircle. The rotating mirror directs the modulated light source along the semicircular ends of the fiber bundles. As the light is focused on the end of each fiber, it is transmitted along the fiber to the surface of the film. Each fiber is illuminated in turn, causing the light to scan the surface of the film and film is advanced after each single scan. Using the fiber optic bundle as described is a method of compensating for the nonlinear scan of the rotating mirror flat bed scanner technique. This approach has the disadvantage of limited resolution capability.

Helical Mirror Scanner

The helical mirror scan reproducer is illustrated in Figure A.1.2.1-1. This novel approach is currently under development by Radiation Systems Division. A helical mirror is mounted on the surface of a rotating drum. The laser beam is collimated and directed along the top surface of the drum as illustrated. The beam is reflected from the surface of the helical mirror and projected onto the film. As the drum rotates, the reflected beam scans the surface of the film. The laser beam is modulated as it scans the surface of the film, reproducing the line of data. The film is advanced after each rotation of the drum thereby producing consecutive scans. This approach has the advantages of a flat bed, variable-length copy; however, it has limited resolution capability.

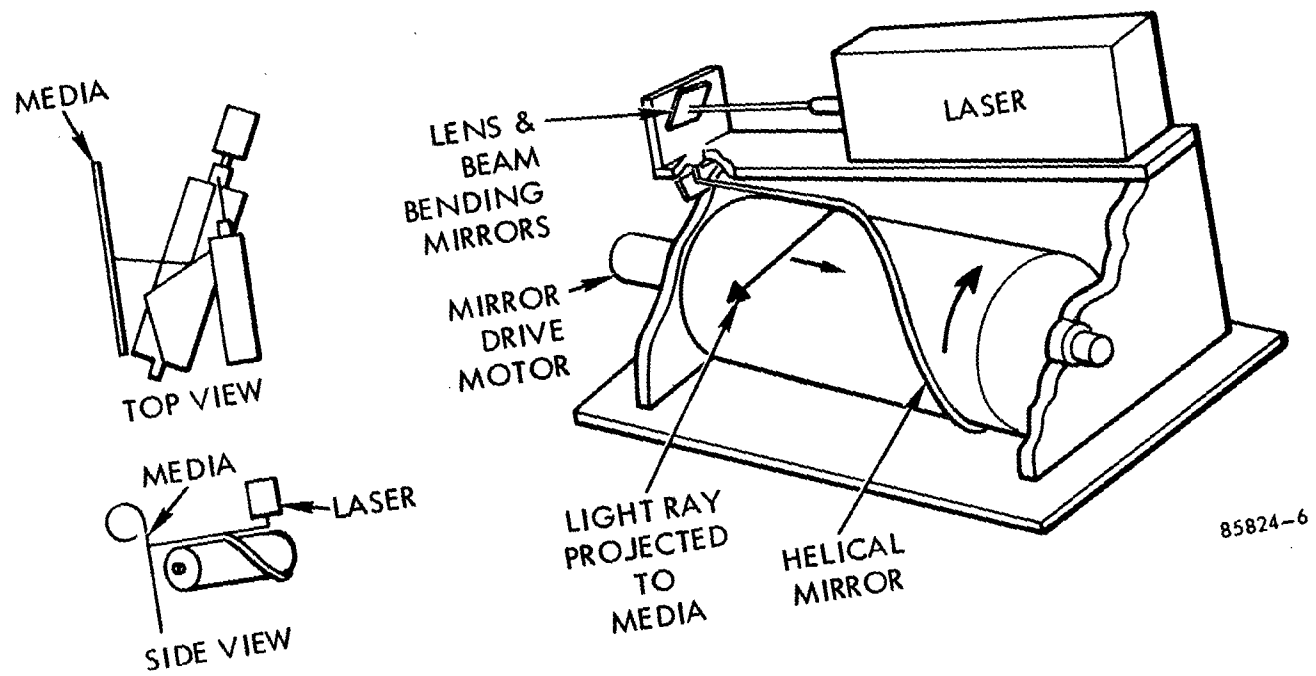


Figure A.1.2.1-1. Helical Mirror Scan Reproducer

Factors to be considered in evaluating the various reproducing techniques which have been summarized are presented in tabular form in Table A.1.2.1-1. The factors listed include the type of reproducer, the resolution, the film processing method available, and the estimated cost.

A.1.2.2 CRT Type Scanners

The previously discussed scan techniques fall into two distinct classes; namely, those that use direct light sources (lasers, for example) and those that employ cathode ray tubes. Although the laser type scanners provide higher resolution (10,000 elements per 9 inch line for the drum scanner) than do CRT scanners, most have the disadvantage of single frame reproduction.

Often system requirements dictate that many successive frames of data or a long continuous strip be printed in real time. This requirement, when coupled with the fact that the superior resolution capability of laser type scanners is not always needed, results in heavy usage of CRT scanners. One additional advantage, that is seldom considered, is that the optics which project the CRT image onto the film can also afford magnification. Thus, a given length CRT line can be printed as a photographic line of any length desired. This frees the print dimensions from the scanner dimensions and allows the scanner selection to be made on the basis of other scanner parameters.

Because of the importance of cathode ray tubes to display technology, the devices offered by several major vendors have been tabulated in Table A.1.2.2-1. Since resolution (element size) is constrained primarily by the CRT spot diameter, the most significant parameter shown is spot size. It is important to remember, however, that magnification increases spot size, and therefore reduces resolution, so that a 1 mil spot on a 4 inch tube provides no better resolution than a 2 mil spot on an 8 inch tube; both yield 4000 elements per line.

A.1.2.3 Recording Media and Processing Techniques

A wide variety of both films and papers are available as the recording media. Table A.1.2.3-1 contains a listing of some of the more commonly used wet processing materials. All of the materials listed in the table are high quality silver type media. The electrostatic, electro-chemical, and pressure-sensitive materials used in low resolution facsimile do not have sufficient resolution or grey scale quality for the application hypothesized.

Table A.1.2.1-1. Scan Technique Comparison

Reproducer Type	Resolution Capability (Elements/line) (9 x 9" Copy)	Auto or Manual Film Processing	Estimated Minimum Cost for 2000 x 2000 Element 9 x 9	Estimated Minimum Cost for 3000 x 3000 Element 9 x 9
Drum	over 10,000	Manual Auto	5 K 15 K	10 K 20 K
Rotating Mirror Flat Bed	5,000	Manual Auto	25 K	25 K
Rotating Mirror Curved Bed	over 10,000	Manual Auto	15 K	20 K
CRT Line Scan	4,000	Manual Auto	10 K	30 K
CRT Raster Scan	4,000	Manual Auto	8 K 15 K	30 K 45 K
Fiber Optics	4,000	Manual Auto	10 K 25 K	12 K 27 K
Helical Mirror	3,000	Manual Auto	5 K 20 K	10 K 25 K

Table A.1.2.2-1. High Resolution CRT's

Model	Size Useful Area	Spot Size @ 5 μ A	Beam Current	Anode Voltage	Approximate Price	Deflection/ Focus
SYLVANIA						
SC 3850 F/O	4 x 1/4	.8 mil	40 μ a	10 KV	\$2400	M/M
SC 3507 F/O	(8-11/16") x 1/4"	2 mil	40 μ a	20 KV	\$2400	M/M
SC 3800 F/O	(8-11/16") x 1/4"	5 mil	20 μ a	10 KV	\$3700	M/E
SC 3876 F/O	(8-11/16") x 1/4"	4 mil	20 μ a	10 KV	\$3700	M/M
SC FP	4.25 dia	1.5 mil	10 μ a	10 KV	\$ 400	M/E
FAIRCHILD-DUMONT LABS						
K-1871	5" tube	.7 mil @10 μ A	1-100 μ a	25 KV	\$2800	

Table A.1.2.2-1. High Resolution CRT's (Continued)

Model	Size Useful Area	Spot Size @ 5 μ A	Beam Current	Anode Voltage	Approximate Price	Deflection/ Focus
FAIRCHILD-DUMONT LABS (Cont'd)						
KC-2691	6.25" tube	1 mil @10 μ A	1-100 μ a	25 KV	\$1800	
2373	9" tube	2 mil	1-100 μ a	25 KV	\$1600	
FERRANTI ELECTRIC						
5/71 AP	4.3125 dia	.3 mil	40 μ a max	25 KV	\$1400	M M & E
5/71 Q	4.3125 dia	.7 mil	40 μ a	25 KV	\$1400	M M & E
9/71	8.4375 dia	.8 mil	40 μ a	25 KV	\$2200	M M & E
5G/75 PM	4.3125 dia	.4 mil	40 μ a	25 KV	\$1400	M M & E
WESTINGHOUSE						
WX-4903 P-11	4.25 x .25	.65 @ 1 μ a	100 μ a	15 KV	\$2600	M/E
WX-30315 P-11	6.25"	1.5 @ 1 μ a	100 μ a	15 KV	\$1400	M/M
WX-31224 P-11	1"	1.7 @ 4 μ a	100 μ a	10 KV	\$ 350	M/E

Table A.1.2.2-1. High Resolution CRT's (Continued)

Model	Size Useful Area	Spot Size @ 5 μ A	Beam Current	Anode Voltage	Approximate Price	Deflection/ Focus
LITTON INDUSTRIES						
L-4210 (4186) Full Screen	8" dia	1.0 mil	90 μ a max	25 KV	\$4100	M/M
L-4167 Line scan With or W/O Fip Op	8125" dia	1.25 mil	600 μ a max	25 KV	\$4100	M/M
L-4192	8.325" dia	1.5 mil	90 μ a max	25 KV	\$3500	M/M
L-4186	9.25" dia	1.25 mil	600 μ a max	25 KV	\$4100	M/M
L-4114	4.24" dia	1.2 mil	90 μ a max	20 KV	\$1600	M/M
L-4123	4.25" dia	.85 mil	90 μ a max	25 KV		M/M

Table A.1.2.3-1. Typical Wet Processing Recording Media

Type	Base	Speed	Processing	Maximum Density Range
Kodak KIND 2083	RC, Paper	Extended Red	3 Bath	Above 2.0
Kodak RAR-6479	Mylar	Extended Red	3 Bath	Above 2.0
Kodak SO-200	Mylar		Monobath	Above 2.0
Kodak RAR-2491	Mylar		3 Bath	Above 2.0
Kodak KIND 1931	RC, Paper		3 Bath	Above 2.0

A large amount of work is being done in dry process recording media and Table A.1.2.3-2 reflects the variety of dry process media currently available. In general, the dry process media have high resolution capabilities and a fairly wide range of gamma distribution. They do have the drawback, however, of having an extremely steep gamma curve that makes controlling the exposure level more difficult. Development processes, particularly heat, for these media are extremely difficult to control and obtain uniform results. Papers are also characteristically in the low-speed range that requires a very intense light for exposure. The high-intensity light requirement, the difficult-to-control processing, and media stability are problems which are holding back the dry processing techniques. Thus far, the results obtained with dry processing techniques are inferior to those obtained with wet processing media and techniques.

The wet film process is that normally used for black and white photographic work. It can be of the three-bath type or the monobath type. The three-bath type consists of the developer, the stop bath, and the fixer. The monobath process utilizes a special recording media which is processed and fixed in one pass through the solution. Both techniques require a washing and drying operation after the development cycles. Wet process development can be either manual or automatic. For those applications requiring relatively few copies to be processed, a more economical solution is to remove the exposed copy from the machine in a darkened room and develop it off-line. There are a number of low-cost automatic processors available to perform this off-line development. Fully automated processing techniques are essential where the reproduction rate is high and there are a number of reproducing machines available with fully automated processing. Most of these processors use multibath processing. Some of the processors are built to handle sheet film and paper, while others are built to handle a continuous roll of film or paper.

A.1.2.4 Annotation

It is often desirable to print ancillary information on the photographic negative along with image data. Typically, this might include mission numbers, ground station designator, approximate geographical location of image, course data/time information, and precise time flags. In the case of a CRT type scanner, this information is easily programmed into a character generator and can be scanned on a line-by-line basis along with the image by the CRT. Either type scanner could use a separate CRT, character generator, and set of optics to focus the characters on the film. In fact, any method can be used to write or display the desired characters (for example nixie readout or computer printer) and the plane upon which they are written imaged in the film margin via a set of annotation optics.

Table A.1.2.3-2. Dry Process Recording Media

Type	Base	Speed in ERGS/CM ²	Processing	Maximum Density Range
Kalvar	Film	10 ⁶	Heat	1.1
Dupont Dylux	Film	3 x 10 ⁶	Light	Above 2.0
Horizons Free Radical	Film	10 ⁵	Light and Heat	Above 2.0
Kodak KIND 1991	Paper	2 x 10 ²	Heat and Light	1.1
3M Dry Silver	Paper	3 x 10 ³	Heat	1.9
3M Dry Silver	Film	3 x 10 ⁴	Heat	Above 2.0

A.1.2.5 Signal to Noise Ratio

A reasonable requirement for an optical system signal to noise specification would be that the RMS value of the signal exceed the RMS value of the noise by a factor of 3 (9.5 dB) for the minimum signal level to be displayed. For a system capable of displaying 16 equal grey shade levels, the ratio of maximum to minimum signal amplitude is 24 dB. Thus, a system that provided an RMS/RMS signal-to-noise ratio of 33.5 dB would meet the requirement. Signal-to-noise ratio in optical systems is typically expressed in terms of the ratio of peak-to-peak signal amplitude to RMS noise amplitude. For a sinusoidal signal, the peak-to-peak to RMS ratio is 9 dB. Adding 9 dB to 33.5 dB results in a peak-to-peak signal to RMS noise ratio requirement of 42.5 dB at the display.

A.1.2.6 Digital versus Analog Displays

The relative advantages of digital and analog signal forms are often discussed with respect to communication channel performance. In a similar manner, the two signal forms impact the design and performance of a display system. Before considering the effect of signal choice on the display, it is important to note that a digital or analog communication channel does not necessarily require a respective digital or analog display system. Rather, A/D or D/A conversion can be accomplished between the channel output and the display input and thus allow any combination of the two signal forms that appears advantageous to the system as a whole.

The most common form of CRT display uses analog signals to intensity modulate an electron stream which is scanned across the tube face via deflection circuits that are driven by analog voltage or current waveforms. Similarly, intensity modulated laser beams are scanned across an image plane through the use of analog deflection waveforms. The combination of electron beam current (or laser beam intensity) and dwell time determine the excitation imparted to a given element on the image plane. Dwell time in turn is controlled by scan velocity which is generally linear with time. Corrections for such phenomena as CRT nonlinearity (flat image plane instead of curved), geometric distortions resulting from the curved earth, satellite altitude changes, or distortions inherent in the satellite scanner must be achieved by variation of the scan velocity during each scan. Since scan velocity is controlled by an analog waveform, the correction of several complex nonlinearities often results in a difficult waveshape generation problem. When few or no corrections are required, however, analog displays are generally simpler and somewhat less expensive than digital displays.

Since the light intensity of a CRT element is a function of the product of beam current and time, the illumination of a given element can be varied by switching the beam current off and on with the on-time over a particular element location controlled by a digital word. This approach has several advantages. A digital line of data can easily be stored, processed, and corrected in a small special purpose computer which allows the scan/imaging portion of the display to be kept extremely simple. The spatial position of a given element can be shifted along a line (to correct for nonlinear image distortion for example) by moving the digital word in time. Line compression can be achieved by deleting or averaging samples, and line expansion by inserting repeated or averaged samples between the actual data samples; both compression and expansion of line length are important operations in correcting for scale errors. Similarly, roll correction can be accomplished with a simple timing change that shifts the samples of an entire line relative to the display center and starts the scan on an earlier or later sample. Another advantage of a digital display is that mission parameter changes can be accommodated with relative ease by changing the display software. As an example, one might consider the replacement of a constant angular velocity scanner in the spacecraft with one that has harmonic motion.

Because of the ease with which digital signals are stored, processed, and manipulated, digital display systems are advantageous where many operations are to be performed on the display signal prior to imaging. The precise timing and computational ability of even small special purpose computers allows the generation of extremely accurate correction curves for missions that require preciseness in image location and scale. In situations where image location and scale errors are small, or moderate distortion is tolerable, the simplicity and lower cost of the analog display may yield advantage.

A.1.3 System Parameter Relationships

The design of display segment components to satisfy the demands of a given optical mapping system is heavily dependent upon other parameters within the system. Several of the major systems considerations that impact display requirements are discussed below.

A.1.3.1 Frame Size

The earth dimensions of the region to be photographed impact both the resolution and the scale of the photographic negative produced. The negative frame size is seldom greater than 12 inches wide because of difficulty in imaging data over a large area with low distortion. In the case of a CRT type scanner, the number of discrete intensity elements that can be displayed on a scan line is limited by the spot size of the tube; thus, a 4 inch tube with a spot diameter of 1 mil can display 4000 elements per line. If the earth dimension of the frame is 100 nautical miles, the minimum possible earth distance that can be displayed is 1/40th of a nautical mile, or about 45 meters. If the 4 inch CRT image were magnified by a factor of 3 to provide a 12 inch negative, the photographic scale would be 12 inches to 100 nm or 1:608,000. Since the image element size is magnified the same as the frame size, magnification does not effect ground resolution.

A.1.3.2 Display Resolution

The ground resolution of a display is generally expressed in units of optical line-pairs per unit distance, where an optical line is equivalent to two TV lines. Since, the width of a TV-line is equivalent to the CRT spot size, the width of an optical line for the example discussed above would be 2 mils on the CRT or 1/20th of a nautical mile on the earth; this corresponds to the width of 2 display elements. In order to remove ambiguity, it is necessary for a display element to be somewhat smaller than the smallest object to be resolved; typically the ratio (called Kell factor) is selected to be $\sqrt{2}$. Thus, the width of a resolution cell (2 resolution elements) is $2\sqrt{2}$ times the width of the display spot size. For the example parameters then,

$$\text{display resolution} = 2\sqrt{2} \text{ mils/line-pair}$$

or

$$\text{ground resolution} = \sqrt{2}/10 \text{ nautical miles/line-pair}$$

Alternately, resolution may be expressed as the inverse of that given above or,

$$\text{display resolution} = \frac{1000}{2\sqrt{2}} \quad \frac{\text{line-pairs}}{\text{inch}}$$

or

$$\text{ground resolution} = \frac{10}{\sqrt{2}} \quad \frac{\text{line-pairs}}{\text{nautical mile}}$$

Before proceeding, it is important to note that the resolution computed above is actually a bound on the best that can be achieved for the parameters given. That bound will be degraded by the performance limitations of physical components within the display as well as those in other parts of the system.

A.1.3.3 Modulation Transfer Function

Performance of optical systems are often measured as a function of the smallest alternating black-white pattern that can be detected, where the combined width of a black plus a white element is called a resolution cell or resolution cycle. This evaluation criterion adds a frequency characteristic to the optical signal in the space domain. This characteristic has units of cycles per unit distance and is typically called "spatial frequency". Thus, the impact of system components upon the optical signal can be considered in terms of frequency response as is common in electrical waveform analysis.

If the spatial distribution of radiance for an object to be photographed is defined as the object function $o(x)$, and the spatial distribution of radiance for the photographic image of that object is defined as the image function, $i(x)$, the two are related in the space domain by the system point spread function, $s(x)$, through the relationship:

$$i(x) = s(x) * o(x)$$

where $*$ indicates convolution.

By taking the Fourier transform of both sides, the expression can be converted to the frequency domain as,

$$S(\omega) = \frac{I(\omega)}{O(\omega)}$$

where $S(\omega)$ is analogous to the transfer function in the circuit analysis. The normalized value of $S(\omega)$ is called the optical transfer function.

$$T(\omega) = \frac{S(\omega)}{\int_{-\infty}^{\infty} s(x) dx}$$

Since most optical systems operate with non-coherent light, only the magnitude of the transfer function is important. Thus, modulation transfer function (MTF) is defined as,

$$T(K) = \left| T\left(\frac{\omega}{2\pi}\right) \right|$$

where K = optical frequency in cycles/unit distance.

Since optical components have finite frequency responses, the amplitudes of optical waveforms are reduced as frequency content increases. The frequency at which the amplitude of an optical black-white pattern is sufficiently attenuated by the composite system MTF to make the pattern indiscernible is another limit on system resolution. The MTF of a system is computed as the product of the transfer functions of individual series components. That is, series system components affect the "optical bandwidth" of the system precisely as limited bandwidth components do in a communication channel.

Previously, the diameter of the CRT spot was considered as a limit on system resolution. The spot was treated as though its intensity were uniformly distributed in space, where in reality that distribution is more nearly Gaussian. If spot diameter (and therefore element size) is defined as the 50 percent point on the Gaussian spot, some of the element information will spill over into the region occupied by adjacent elements. This spreading effect (really a form of intersymbol interference) is a contributor to the total MTF of the system.

In a similar manner, the spacecraft scanner lens makes an MTF contribution. The diffraction limited resolving power of a lens (or reflector) defines the best possible resolution achievable by that lens; it is generally referred to as the Rayleigh criteria:

$$\theta = \frac{1.22\lambda}{D}$$

where θ = minimum resolvable angle

λ = wavelength of light

D = diameter of lens

and

$$\text{ground resolution} = \frac{1}{h \theta} \left(\frac{\text{cycles}}{\text{unit distance}} \right)$$

where h = satellite altitude.

Other contributors to the system MTF include the film used in the display, the contrast range of the system, the grey level resolution required, and the video bandwidth of the communication channel. Each has the effect of reducing system response to higher frequency optical waveforms and thus limits the maximum number of cycles per nautical mile (or conversely the fraction of a nautical mile per cycle) that the system can resolve.

A.1.4 Communication Channel Limitations

Much of the emphasis of this study effort has been upon definition of the communication channel over which the image data is to be transmitted. In fact, using this viewpoint the channel can be thought of as a "bottle neck" in the system which limits the ultimate performance achievable. As a result, it is useful to consider the impact of the channel upon system performance. Accordingly, the analyses below relates system and display parameters of interest to the data rate which can be transmitted with acceptable quality over the channel.

In the interest of achieving numerical results, the dimensionality of the problem will be reduced by constraining several of the system parameters, namely:

Satellite Altitude	- 500 nautical miles
Earth Frame Size	- 100 x 100 nautical miles
Frame Overlap	- 10%

Transmission Mode	- real time, continuous
Channel Type	- digital
Number of Grey Shades	- 16
Digital Data Efficiency	- 90%

It is assumed that satellite data is buffered and that the airborne scanner efficiency and ground scanner efficiency are similar such that data will be displayed at an average rate equal to the transmitted data rate. Allowance for frame overlap makes the computations conservative. Given a digital efficiency of 90%, the data rate is,

$$\text{Data Rate} = 0.9 \times \text{bit rate}$$

The image frame to be transmitted is assumed to consist of an array of $n \times n$ TV-elements ($n/\sqrt{2} \times n/\sqrt{2}$ resolution elements.). By sampling at a rate of 1 sample per TV-element (2.8 samples per resolution cell) ambiguity can be resolved. Thus, the TV-element rate is,

$$\begin{aligned} \text{TV-element rate} &= \frac{0.9 \times \text{bit rate}}{4 \text{ bits/sample} \times 1 \text{ sample/element}} \\ &= 0.225 \times \text{bit rate} \end{aligned}$$

Satellite motion will determine the time available to scan the along-track dimension of the raster; given a 10% frame overlap and a 500 nm orbit (3.5 nm/sec ground trace), the time available to transmit each 100 nm frame is,

$$\text{time/frame} = \frac{90 \text{ nm/frame}}{3.5 \text{ nm/sec}} = 25.7 \text{ sec/frame}$$

The number of TV-elements that are available for each frame is,

$$\begin{aligned} \text{TV-elements/frame} &= \frac{\text{TV-elements}}{\text{Sec}} \times \frac{\text{Sec}}{\text{frame}} \\ &= 0.225 \times \text{bit rate} \times 25.7 \\ &= 5.77 \times \text{bit rate} \end{aligned}$$

Assuming that a symmetrical array of TV-elements make up a frame,

$$\begin{aligned} \frac{\# \text{ TV-elements}}{\text{line}} &= \frac{\# \text{ TV-lines}}{\text{frame}} = \left[\frac{\# \text{ TV-elements}}{\text{frame}} \right]^{\frac{1}{2}} \\ &= 2.4 (\text{bit rate})^{\frac{1}{2}} \end{aligned}$$

Two constraints are placed upon the size of negatives produced by the system. First, display and processing limitations argue for a negative width of less than 12 inches. Second, if the negative image is to be compared to existing maps, a standard scale would be desirable. An image size of 7.3 inches has been selected which results in a scale of $1:10^6$ (or 13.7 nm on the earth transforms to 1 inch on the display). This will allow adequate margins for annotation on a 10 to 12 inch negative.

The number of TV-lines/inch required of the display is,

$$\begin{aligned} \frac{\text{TV-lines}}{\text{inch}} &= \frac{\text{TV-lines}}{\text{frame}} \bigg/ \frac{\text{inches}}{\text{frame}} \\ &= \frac{2.4 (\text{bit rate})^{\frac{1}{2}}}{7.3} = 0.329 (\text{bit rate})^{\frac{1}{2}} \frac{\text{TV-lines}}{\text{inch}} \end{aligned}$$

The diameter of the TV-spot must then be,

$$\text{TV spot diameter (d)} = \left[\frac{\text{TV-lines}}{\text{inch}} \right]^{-1} = 3.04 (\text{bit rate})^{-\frac{1}{2}} \text{ inches}$$

The display resolving power (K_1) is,

$$K_1 = \frac{1}{2\sqrt{2} d} = 0.116 (\text{bit rate}) \frac{\text{optical line-pairs}}{\text{inch}}$$

The ground resolution (smallest resolvable black/white pair) is,

$$\begin{aligned}
 a &= \frac{1}{K_1} = 8.62 (\text{bit rate})^{-1/2} \frac{\text{inches (display)}}{\text{optical line-pair}} \\
 &= 1.18 \times 10^2 (\text{bit rate})^{-1/2} \frac{\text{nm (ground)}}{\text{optical line-pair}} \\
 &= 2.19 \times 10^5 (\text{bit rate})^{-1/2} \frac{\text{meters (ground)}}{\text{optical line-pair}}
 \end{aligned}$$

The scan rate required of the system is,

$$\begin{aligned}
 \text{scan rate} &= \frac{\text{TV-lines}}{\text{frame}} \frac{\text{sec}}{\text{frame}} = \frac{2.4 (\text{bit rate})^{1/2}}{25.7} \\
 &= 9.35 \times 10^{-2} (\text{bit rate})^{1/2} \frac{\text{TV-lines}}{\text{sec}}
 \end{aligned}$$

The display parameters computed have been evaluated for several bit rates of interest and their values are shown in Table A.1.4-1. Although a digital communication channel was used as an example, the results for an analog channel would be similar. A close approximation of the video bandwidth required for an analog channel is 1/8th the bit rate shown for the digital case. Several of the system parameters were fixed before the effects of bit rate upon display requirements were evaluated. The impact of such parameters as vehicle altitude (and therefore ground trace velocity), earth frame size, and the number of grey shades required are obvious from their use in the above computations.

Examining the display performance and requirements shown in Table A.1.4-1, it is seen that an order of magnitude improvement in ground resolution (700 meters/line-pair to 70 meters/line-pair) is achieved when the bit rate is increased from 100 Kbps to 10 Mbps. Although it may be feasible to dedicate a 10 Mbps channel to the mission, several of the associated parameters required to achieve a resolution of 70 meters/line-pair are beginning to approach the limit of presently available hardware capabilities (for the 100 mile frame).

Considering the CRT data of Table A.1.2.2-1, it is found that only two 8 inch tubes will provide a spot diameter of 1 mil or less; the Ferranti 9/71 and the Litton L-4210. Assuming a magnification of 2:1, two of the 4 inch tubes listed provide spot diameters of less than 0.5 mil and could also meet the 70 meter requirement; the Ferranti 5/71 AP and 5G/75 PM. Although laser scanning devices can achieve smaller spot diameters than needed, the inertia inherent in mechanical

Table A.1.4-1. Display Parameters

Parameter	Parameter Value				Units
	Case 1	Case 2	Case 3	Case 4	
Bit Rate (BR)	10^5	10^6	4×10^6	10^7	bps
TV-element rate	2.25×10^4	2.25×10^5	9×10^5	2.25×10^6	$\frac{\text{elements}}{\text{sec}}$
# elements/frame	5.77×10^5	5.77×10^6	2.31×10^7	5.77×10^7	
Scan Rate	29.7	93.5	187.0	297	$\frac{\text{TV-lines}}{\text{sec}}$
# TV-lines/inch	104	329	658	1040	$\frac{\text{TV-lines}}{\text{inch}}$
TV-spot diameter (d)	9.60	3.04	1.52	0.960	mils/element
Resolving Power (K_1)	36.8	116	232	368	$\frac{\text{line-pairs}}{\text{inch}}$
Ground Resolution ($a = 1/K_1$)	0.374 695	0.118 219	0.059 110	0.037 69.5	Nm/line-pair meters/line pair

scanning techniques would make the required scan rate of 297 TV-lines/sec difficult to achieve in a continuous strip type display.

Another consideration that should be examined is the resolution capability of the viewer. Under the most favorable conditions of contrast and background luminosity, it is difficult for the human eye to resolve an angle smaller than approximately 0.6 arc minutes. Assuming a viewing distance of 10 inches, this converts to an element size of 1.75 mils. Thus, the spot diameter of the system that provides 70 meter resolution is considerably smaller than can be resolved by the viewer and may indicate a waste in system resources.

The fact that display components are beginning to approach the limits of their capability for the highest bit rate considered indicates that an effort to reduce the demands made of those components may be valuable. Although CRT

type scanners can achieve higher scan rates than mechanically scanned laser scanners, the minimum spot size achievable is considerably larger. One of the constraints previously placed on the display was that it be capable of printing continuous frames of image data in real time. If this constraint were removed, the data could be recorded during a pass and played back for printing at a lower rate (either continuously or one frame at a time). This change would make several of the laser scanning techniques competitive and yield advantages that include simpler and less expensive scanners (the drum scanner for example), smaller spot size, and the ability of the system to handle higher information rates. Thus, recording could increase the limit placed upon system resolution by the display and/or allow the use of display components that were not operating near the limit of their capability.

A.1.5 Mislocation Errors

The precise geographical location of a point within a given photograph may be extremely important to some classes of users. As such, it is of interest to consider some of the major sources of mislocation error within the system and attempt to estimate a value for each.

A.1.5.1 Projection Error

Referring to Figure A.1.5.1-1, if the system scans the true earth arc "OB" but assumes that the flat earth distance "OA" was scanned, an obvious error results. Given as functions of the satellite scan angle from nadir (β), the satellite altitude (h) and the radius of the earth (H) the two distances are:

$$OB = S_{ce} = H \left[\sin^{-1} \left(\frac{h + H}{H} \sin \beta \right) - \beta \right]$$

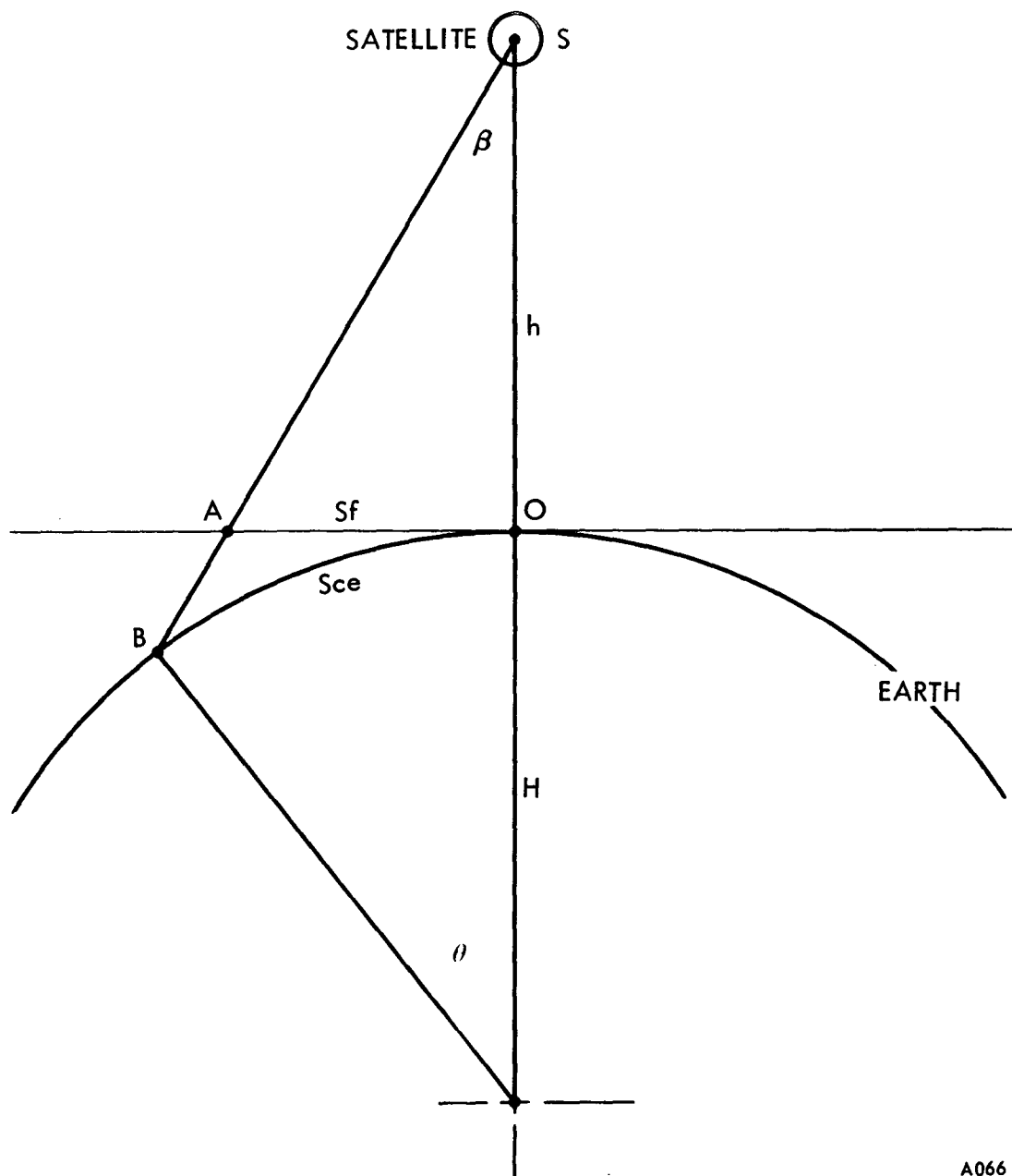
$$OA = S_f = h \tan \beta$$

For a center to edge earth distance of 50 nautical miles, β equals 5.7 degrees and the ratio of cross-track earth distance (S_{ce}) to flat distance (S_f) is,

$$S_{ce}/S_f = 1.00076$$

and the error resulting from the approximation is,

$$\begin{aligned} \text{error} &= -7.6 \times 10^{-4} \times 50 \text{ Nm} = -3.75 \times 10^{-2} \text{ Nm} \\ &= -70 \text{ meters} \end{aligned}$$



A066

Figure A.1.5.1-1. Scan Geometry

For a 100 Nm square frame (50 Nm from center to edge) the error is small and for most practical purposes can be neglected. However, as the frame size is increased above 100 Nm this error quickly becomes significant. Figure A.1.5.1-2 shows the ratio of $S_{ce}:S_f$ for half frame distances up to 100 nautical miles.

The error just discussed occurs in the cross-track dimension of the display raster. If the satellite uses a direct type scanner, great circle arcs will be scanned. Display of these converging arcs as parallel horizontal lines results in an along-track error that is zero at the display center and maximum at the edge. For the small scan angle (β) of the system considered, the ratio of along track distance at nadir (S_{ao}) to along-track distance at the display edge ($S_{a\theta}$) is closely approximated by,

$$\frac{S_{ao}}{S_{a\theta}} = \frac{1}{\cos \theta}$$

where:

θ = the geocentric earth angle between nadir and the display edge.

For a center to edge distance of 50 nautical miles, $\theta = 1.175$ degrees and,

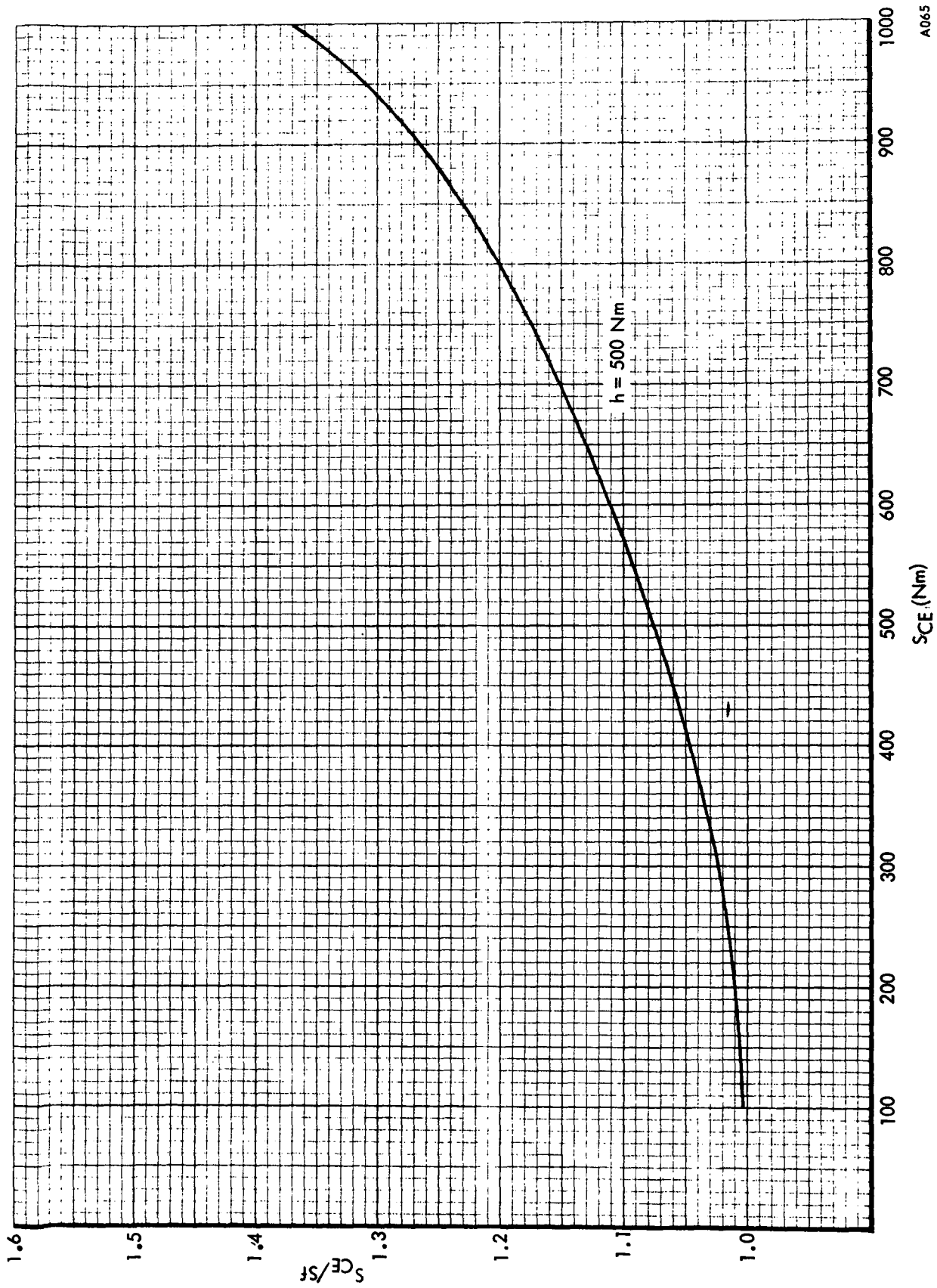
$$\frac{S_{ao}}{S_{a\theta}} = 1.00021$$

Thus, for a 100 nautical mile frame, an along-track end-to-end error of -0.02 nm (37 meters) results.

A.1.5.2 Altitude Error

Variation in true earth distance with changes in satellite altitude are obtained by taking partial derivatives of the distance equations for each dimension. The respective variation equations for the cross-track and along-track dimensions are:

$$\Delta S_{ce} (\Delta h) = \frac{\partial S_{ce}}{\partial h} \Delta h = \left\{ \frac{\sin \beta}{\left[1 - \frac{h+H}{h} \sin^2 \beta \right]^2} \right\} \Delta h$$



A065

Figure A.1.5.1-2. Ratio of Curved to Flat Earth Distance

$$\Delta S_{ae}(\Delta h) = \frac{\partial S_{ae}}{\partial h} \Delta h = -3/2 \left[\frac{H^2 g^{1/2} t}{(h+H)^{5/2}} \right] \Delta h$$

where:

g = acceleration of gravity

t = time/frame

h = change in altitude from nominal

Evaluating both equations for a frame size of 100 nautical miles and a frame period of 25.7 seconds,

$$\Delta S_{ce}(\Delta h) = +0.1001 \Delta h$$

$$\Delta S_{ae}(\Delta h) = -0.034 \Delta h$$

Thus, for an uncertainty of say $\pm 1\%$ in satellite altitude (± 5 nm), the respective cross-track and along-track errors are,

$$\Delta S_{ce}(\Delta h) = \pm 0.5 \text{ nm} = \pm 926 \text{ meters}$$

$$\Delta S_{ae}(\Delta h) = \pm 0.17 \text{ nm} = \pm 316 \text{ meters}$$

A.1.5.3 Spacecraft Attitude Errors

Both pitch and roll errors impact data location by the same magnitude at nadir through the expression,

$$\text{Error} = h \tan \alpha$$

where α is either the pitch or the roll error.

Although the magnitude of a roll error is slightly greater at the frame edge than at nadir, the difference is small (about 3%) for the 100 nm wide frame assumed and can be neglected. A pitch error transforms to a location error along-track while a roll error effects location in the cross-track dimension.

An error about the yaw axis results in location error both along-track and cross-track. Assuming the point of interest to be at the frame edge, the errors are,

$$\text{along-track yaw error} = \pm \frac{A}{2} \sin \gamma$$

$$\text{cross-track yaw error} = - \frac{A}{2} (1 - \cos \gamma)$$

where:

A = frame width

γ = yaw error

For a satellite altitude of 500 nm and pitch, roll, and yaw errors of 0.1 degree, the respective position location errors would be:

along-track error (pitch)	=	$\pm 0.873 \text{ nm}$
	=	$\pm 1620 \text{ meters}$
along-track error (yaw)	=	$\pm 0.087 \text{ nm}$
	=	$\pm 162 \text{ meters}$
cross-track error (roll)	=	$\pm 0.873 \text{ nm}$
	=	$\pm 1620 \text{ meters}$
cross-track error (yaw)	=	$- 7.6 \times 10^{-5} \text{ nm}$
	=	$- 0.14 \text{ meters}$

Note that EOS is expected to be considerably more stable and thus the errors will be reduced. Also, transmission of the S/C orientation can provide capability for corrections via ground processing.

A.1.5.4 CRT Linearity

The direct scan technique assumed for the satellite scanner collects data linearly with time. That is, since the scan is linear in time ($d\beta/dt = \text{constant}$), the same number of data samples are collected for an incremental change in β at the frame edge. This effect results in distance compression in the cross-track dimension that is described by the relationship.

$$\text{Satellite scanner distance compression} = \frac{\beta_m}{\tan \beta_m}$$

where β_m is the maximum off nadir angle scanned.

In a similar manner, a flat face CRT display expands the time linear data received according to,

$$\text{CRT display distance expansion} = \frac{\tan \psi}{\psi}$$

where:

ψ = the CRT off axis angle required to point to the edge of the image.

Thus, the net system distance expansion (+) or compression (-) error from center to edge is,

$$\text{error} = A/2 \left(\frac{\beta_m}{\tan \beta_m} - \frac{\tan \psi}{\psi} \right) - 1$$

where:

A = frame width

For a 500 nautical mile Satellite and a frame width equal to 100 nautical miles on the earth surface, β_m is 5.7 degrees. A typical CRT may have a scan half angle of 15 degrees. In that case, the error would be,

$$\text{error} = + 1.0 \text{ nm}$$

Although many of the errors discussed can be corrected, most corrections are extremely difficult and costly. In the case of CRT linearity, however, the error is easily and inexpensively reduced by shaping the scan waveform. As a result, this error is more reasonably budgeted somewhat lower than the value computed or,

$$\begin{aligned} \text{error residue} &= + 0.2 \text{ nm} \\ &= + 370 \text{ meters} \end{aligned}$$

A.1.5.5 Film Wander Error

Assuming that a line type CRT is used to illuminate a continuous strip of display film, the amount that the film is allowed to wander off center transforms directly to a cross-track error. Close tolerances afforded by modern tension drive systems can assure that film wander will be less than ± 0.01 inches resulting in an error due to this source of ± 0.14 nautical miles (260 meters).

A.1.5.6 Film Advance Error

Whether the film is advanced one line at a time with a precision stepper motor or driven at a constant velocity, the film advance error can be kept to less than 0.5 percent. This tolerance results in an end-to-end along-track error of ± 0.25 nautical miles (463 meters).

A.1.5.7 Film Expansion with Temperature

The fact that film may be exposed at one temperature but viewed at another is also a source location of error. The coefficient of thermal expansion for mylar type film is 1.5×10^{-5} per degree F. Assuming a maximum temperature range of 100 degrees F, the maximum end-to-end along-track and center-to-edge cross-track errors are:

$$\begin{aligned}\text{error (along-track)} &= \pm 0.15 \text{ Nm} \\ &= \pm 223 \text{ meters} \\ \text{error (cross-track)} &= \pm 0.06 \text{ Nm} \\ &= \pm 111 \text{ meters}\end{aligned}$$

Values for the several error contributors considered have been tabulated in Table A.1.5-1 for convenience. The sources of the various location errors are sufficiently independent to warrant RSS combination rather than direct addition. As can be seen, the cross-track and along-track mislocation errors were both computed to be approximately 1 nautical mile. However, it should be noted that the along-track error was computed on the basis of a 100 nautical mile frame length (i.e., end-to-end) where the cross-track error was computed on the basis of center-to-edge distance (50 nm). This difference resulted from the assumption that location of the frame center will be known and used as the reference point for all cross-track distance measurements.

Examination of the mislocation budget shows that the errors in both dimensions are dominated by the spacecraft attitude error assumed, indicating that considerable improvement in location accuracy could be achieved by tightening the tolerance on attitude. Other major contributors such as film wander and CRT linearity in cross-track, and film advance in along-track, could be reduced by improving tolerances beyond those assumed for the budget.

Although the parameter values assumed for the computation of each error contribution are considered reasonable, it should be noted that actual values for a given system may differ considerably from those chosen for this example. In light of that fact, it is important that application of the error values computed be constrained by close comparison of true system parameters to those assumed herein.

Table A.1.5-1. Mislocation Error Budget

Error Source	Cross-Track Error (Meters)	Along-Track Error (Meters)
1. Projection Error	- 70	- 37
2. Altitude Error	± 926	± 316
3. Spacecraft Attitude Error		
Pitch	- - -	±1620
Roll	±1620	- - - -
Yaw	- - -	± 162
4. CRT Linearity Error	± 370	- - - -
5. Film Wander Error	± 260	- - - -
6. Film Advance Error	- - -	± 463
7. Film Expansion with Temperature	± 139	± 278
8. Film Expansion with Humidity	± 111	± 223
Total (RSS) Location Error	1927 meters (1.04 Nm)	1762 meters (0.95 Nm)

A.2 MODULATION AND CODING CONSIDERATIONS

This section presents in summary form important factors relative to the system design. Source encoding which is a technique for reducing the transmitted data rate is discussed in Section A.2.1. Channel encoding is presented in Section A.2.2. Finally, various modulation techniques are discussed and compared in Section A.2.3 on the basis of performance and implementation complexity.

A.2.1 Source Encoding

Source encoding is a form of data processing at the transmission end of the link which has as a goal a reduction in the amount of data to be transmitted. There are many types of source encoding schemes, however, in general the term means to encode at the source of the data in an efficient manner, such that the bandwidth requirements are optimized.

For systems such as the one addressed in this report this is important, since reduced transmission bandwidth can be traded-off against antenna gain, transmission power, and receiver sensitivity. Hence, the cost of hardware to encode and decode may in some cases allow greater savings in other system components.

Efficient source encoding techniques are many and varied and there is no single approach that is a panacea for all data channels. A knowledge of the data to be transmitted (its spectrum and its distribution) and information about its ultimate use are necessary in order to make intelligent decisions as to the engineering tradeoffs available. Source encoding is after all no more than another name for data processing (some prefer preprocessing). If enough is known about the data and its use, some channels could be reduced to mere answers with no need to transmit the data.

In general, source encoding can be split into two classes: (1) entropy preserving codes and (2) entropy reducing codes. The former group implies no loss of information and as such is quite conservative in the amount of reduction possible. These codes generally are of the Huffman class, taking advantage of a skewed statistical distribution of either amplitude samples or run lengths. This type of code has been used with great effectiveness on document facsimile systems where the run lengths of 0's and 1's in a block are coded. The same approach can be applied to picture transmission where the statistics from one element to the next are used. If the differential statistics of a group of six bit digital pictures are studied, a theoretical variable length code can be developed for each picture. The change from one element to the next that occurs most often is assigned a short code while change that seldom occurs is assigned a longer code. Thereby on the average the length

of the code is reduced from the origin 6 bit code. The best that can be obtained however is something over 1 bit per element since something must be transmitted every element. A compact code is thereby produced and is instantaneously, uniquely decodable. By instantaneous it is meant that no delay is needed to determine a code word in a bit stream. The uniquely decodable aspect means that given a bit stream there is one and only one way to pick out code words.

Of many pictures which have been studied by Radiation, two have been chosen as the most and least active. A theoretically optimum statistical code was developed for the active picture and reduced the average number of bits needed for each element to 2.02, while the inactive picture required 1.33 bits per element.

The statistics for many pictures were averaged and a pseudo-optimum code developed. When the code was used on the maximum activity picture 2.05 bits per element were needed. The inactive picture required 1.42 bits per element. This shows that an average code can be developed which will work on many pictures with little penalty beyond the theoretical code.

Another approach to applying entropy preserving codes is bit plane encoding. Here statistics for each level of digital word are studied as a run length. In the most significant bit, there will be many long runs where there is no change and they can be represented by a very short code. A separate code is then developed for each bit level in the digital word. By this method it is possible to reduce the average number of bits required to less than one bit per element for an inactive picture.

Entropy reducing codes are in general more effective if the end use of the data is understood. These are codes which remove redundant information according to some rule or rules when it is needed to reproduce the data on the receiving end to some specified accuracy. The efficiency of these codes is related to the spectral characteristics of the original data and the interpolation process used for reconstructing the data from the transmitted samples.

Many redundancy reduction algorithms exist, however; those which operate on a time waveform are most common. These encoding methods are nothing more than extensions of the sampling theorem, where some means of selecting the transmitted samples is used such that an interpolation process at the receiver can reconstruct the waveform to some predetermined accuracy.

Several types of algorithms exist. In general, however, they may be classed as either predictors or interpolators. Because of the correlation that exists

from sample to sample, a prediction as to the value of the next sample can be made. If the prediction is good enough, there is no need to transmit the sample, since the same prediction can be made at the receiver. Higher orders of digital interpolation processes are really a form of redundancy reduction, in that fewer samples need be transmitted and the interpolation process can add samples at the receiver.

A great deal of research has been done at Radiation on this type of algorithm. Reference [30], Sampling and Source Encoding, explains in detail the operation, implementation, use and problems involved in this type of encoding. Because of diverse user requirements, entropy reducing source encoding is of limited utility for the present application.

Another type of redundancy reduction is where redundancy is compared on a given element in one frame of a picture to the same element in the next frame. For all except the first frame only a difference is transmitted. This method is particularly well suited to the ERTS problem, where the different wavelength pictures can be looked at as a frame. Since the multi-spectral scanner scans all wavelengths at the same time there will be a great deal of redundancy between frames of different wavelengths.

Another possible reduction algorithm which should be considered for multi-spectral scanner output is one which looks at the first frame and the ones that follow in vector space. The raw signals from four channels of the multi-spectral scanner can be considered as four orthogonal functions forming the basis of a four-dimensional vector space. At any instant in time, these four vectors describe a vector in this space whose magnitude and orientation fully define the spectral and amplitude characteristics of the particular spatial resolution element being viewed. Both the amplitude and orientation of this vector vary as the scanner instantaneous field of view moves across the ground. Once this vector is defined as a function of time, there exists a variety of time-varying orthogonal functions within the vector space which can be employed to define the vector as well as the four orthogonal inputs. Therefore, the problem becomes one of defining the proper transform variables within this space, and a means of electronically performing the transformation. A new orthogonal set of functions can then be found such that some of the redundant properties of the data can be removed. This new set of orthogonal functions for the basis of a vector space which is sometimes referred to as the "feature space."

To illustrate the concept, consider the following example. Suppose for simplicity only three wavelengths are used. Denote the three signals as $f_1(t)$, $f_2(t)$, and $f_3(t)$. The vector $F(t)$ has components of each of these. One possible transformation would be to treat f_1 , f_2 , and f_3 as orthogonal vectors and form the radius or length of the vector and two angular components (i.e., the transformation from rectangular to spherical coordinates).

If this is done, it may be possible to transmit the radius component with high quality (full bandwidth and fine quantization). The angular channel data rate could be reduced significantly since it is expected that angular data will change slowly from frame to frame. This technique would be effective if the key signature characteristics have to do with the relative content of the wavelength components, i.e., for certain types of targets areas, amplitude data may vary radically from cell to cell but the relative strengths of various wavelengths may tend to be constant.

It is interesting to note that the technique used in color TV is a particular case of this general procedure where a weighted sum signal is transmitted with high quality and two different signals are transmitted at limited bandwidths.

It is impossible to discuss here all the pros and cons of all applicable source encoding techniques. Each data channel must be examined on its own for proper evaluation. Many studies have been performed on various types of data. As a result of these studies several systems have been implemented with both hardware and software. One of the most significant ones is a classified operational satellite. In this case source encoding is used to reduce many megabits of data to a few hundred kilobits.

Radiation has also designed and fabricated a digital TV communication simulator for NASA/Houston which implements two source encoding techniques. The first is a zero order redundancy remover and the second a differential statistical encoder. The most significant point about this equipment is its operating rate of up to 48 megabits/sec. The simulator allows a rapid assessment of the effect of source encoding on a variety of live data.

As a result of surveying the field of source encoding technology, the following conclusions and observations with respect to image transmission can be made.

1. Source noise must be carefully controlled. In many instances the source noise rather than the data itself limits the amount of reduction achievable.
2. A 2:1 reduction in the bit rate, as compared to PCM, can be achieved without much difficulty. This reduction translates into a 50 percent reduction in both bandwidth and power.* A larger reduction can be achieved at the expense of increased equipment complexity or decreased data quality, or a combination of the two.

*If channel coding is used, a larger power reduction can be achieved at the expense of a smaller bandwidth reduction.

3. The effect of transmission errors on the reconstructed data is not well known. Further experimental work in this area is required; the digital TV demonstration test set previously referenced is a step in this direction.

4. Source encoding of still pictures is definitely feasible, whereas there are a number of questions concerning real-time TV pictures.

5. For real-time television the use of high information delta modulation appears attractive because a minimum of buffering and synchronization is required. Other techniques may also be used, but require a buffer and the associated control logic which render the implementation considerably more complex. The TV demonstration simulator will permit evaluating the feasibility of encoding live TV pictures.

A.2.2 Channel Coding Techniques

Channel coding implies that redundancy is added to the transmitted data in a manner which allows bit errors to be detected and corrected at the receiver processor. This section summarizes the performance and complexity of several classes of codes including the best presently available systems. It is anticipated that in the near future coding performance gains will not be increased appreciably by new techniques but that the complexity and cost will be reduced by LSI technology advances. Maximum bit rates should increase above the present 10 Mb/s capability.

The study concentrated on forward error correcting codes as opposed to systems using error detection and feedback. Obviously, the latter technique is impractical in situations where long time delays are involved, as is the case in almost all space links. Two different forms of channel coding have been studied, block and convolutional coding. For purposes of comparison of various algorithms used to decode these code types, it is assumed that a bilevel bit stream of independent data samples are to be transmitted over a white additive Gaussian noise channel. The performance criterion is then the probability of making decoded bit errors at various or specified signal-to-noise ratios. Since redundancy is added, this signal-to-noise ratio is the energy per data bit divided by the one-sided noise power spectral density; i.e., E_b/N_o . Under these conditions channel encoding can be considered as an entity, independent of the data source and the RF modulation-demodulation techniques.* Performance gains can then be measured with respect to a binary zero

*Strictly speaking, this is true only of memoryless channels, i.e., channels on which bit errors occur independently. In channels which exhibit memory (such as the continuous phase FSK channel with two bit decisions discussed in Section A.2.3, the dependence of bit errors must be taken into account when selecting a code for the channel.

dc waveform transmitted over a baseband channel corrupted by additive white Gaussian noise and detected by integrate-and-dump circuits (i.e., a matched filter).

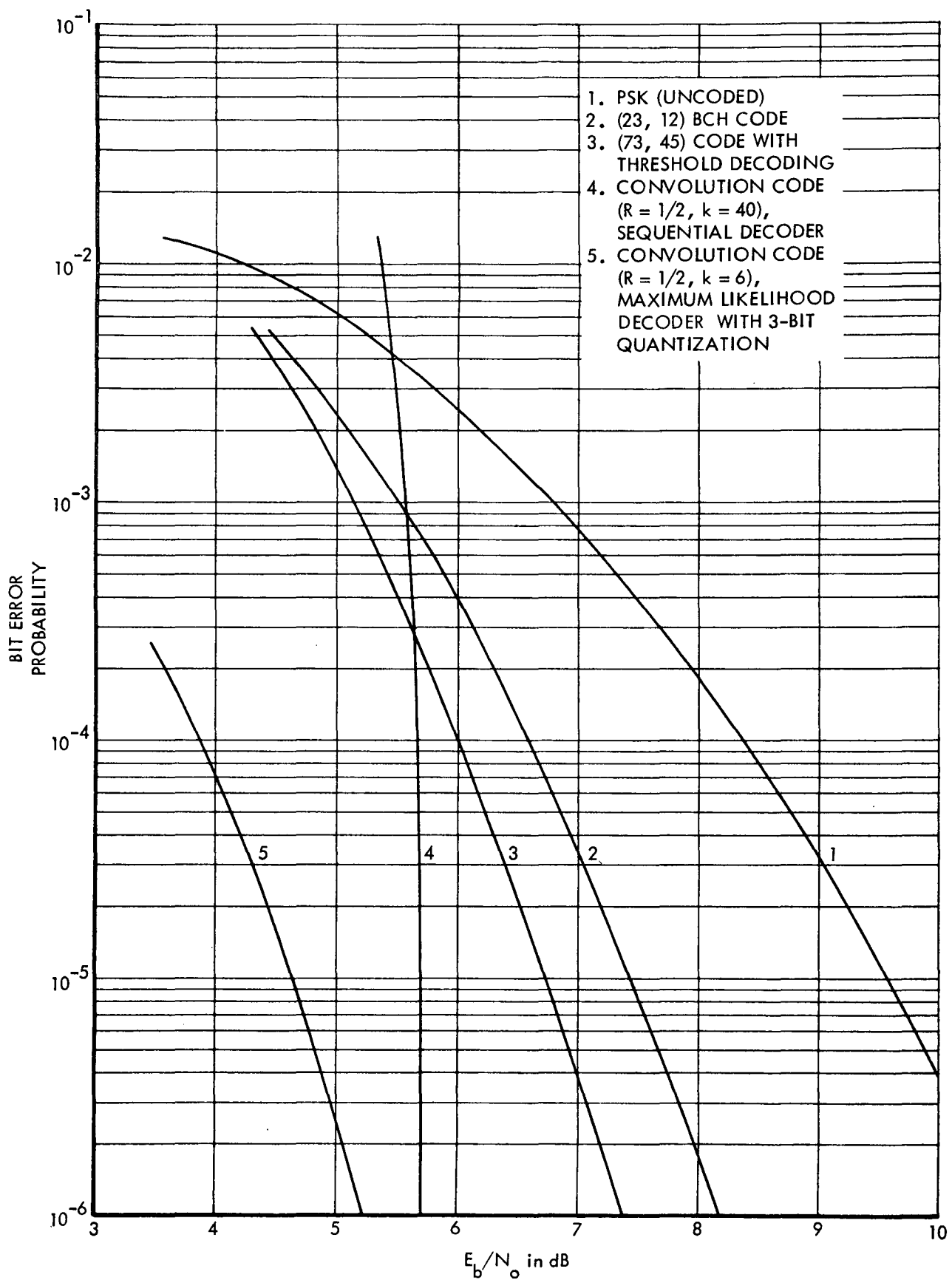
Complexity is measured in terms of the number of integrated circuit packages required, based on components currently available. Several important components such as Read Only Memories or Plated Wire Buffers are given an equivalent number of IC packages based on cost and power consumed.

Assuming a constant bit rate to be transmitted over the channel, as is usually the case, the addition of redundancy increases the required bandwidth. Also, the decoder must operate at the increased bit rate. Thus the bandwidth factor is an important parameter in coding/decoding systems.

The two basic types of codes studied are block codes and convolutional codes. As the name implies, the block coding schemes take a block of K data bits and add $N-K$ redundancy, or parity, bits. Partial specification of a particular code using these definitions is (N,K) . Note that the bandwidth factor is N/K . Convolutional codes add redundancy by continuously operating on the input bit stream to produce a new, higher rate, bit stream with desirable characteristics (i.e., error correcting capability). The performance gain of the convolution coding schemes is determined by the bandwidth factor as well as another parameter, the constraint length K . This constraint length indicates the length of time, measured in number of bits, that a particular data bit will be held in the coding circuitry to directly affect the output bit stream. Increasing k will raise the performance gain at the expense of increased complexity. Figure A.2.2-1 presents typical performance curves for different codes, and Table A.2.2-1 shows the coding gain and circuit complexity for convolutional codes using different decoding techniques, as well as for block codes. The bandwidth factors are also indicated in Table A.2.2-1.

As a result of the study, the following conclusions can be drawn.

1. For a given level of complexity, convolutional codes provide a higher coding gain than block codes. However, the band-spreading factor is also higher than in the case of block codes.
2. At the bit error probabilities of interest, convolutional codes with a maximum likelihood decoder provide the best performance.
3. Coder implementation is simpler for convolutional codes than for block codes.



86115-188

Figure A.2.2-1. Performance of Different Codes

Table A.2.2-1. Summary of Current Channel Coding Hardware and Performance

Decoder	Rate	Coding Gain (dB) $P(E) = 10^{-5}$	Complexity (IC Packages)	Bandspredding Factor
Maximum Likelihood	1 kb/s	6-7	50-100	2
	2.4 kb/s	4.5-5	50-100	2
	200 kb/s	4.5-5	250	2
	9 Mb/s	4.5-5	1900	2
Sequential	1 Mb/s	4.5	700	2
	8 Mb/s	4-4.5	1200	2
AAPP	2 Mb/s	2-3	40-90	2
Block** Codes	10 kb/s	2-3	155-200	5/3, 3/2
	5 Mb/s	2-3	200-300	6/5, 5/3, 3/2

*Memory is converted to equivalent IC Packages

**Includes group sync logic and buffering

4. Coder complexity is relatively independent of data rate, both for block and convolutional codes.

5. The complexity of the decoder increases with the data rate. The increase in complexity with data rate is particularly steep in the case of maximum likelihood decoders. Whereas at low rates maximum likelihood decoders are comparable or simpler than decoders for block codes at data rates below 100 kb/s, they are considerably more complex at higher data rates.

Comparing the coding technology summarized here to the system configuration which has evolved in this study, the most likely candidate for utilization of channel encoding is the Mode II system which transmits directly to local users. Coding would allow increased data rate and therefore resolution and/or a less expensive receiving system. Both are important to the local user. The high data rate of the Mode I system along with apparently adequate link gain make coding

perhaps less attractive for that application. This factor should be considered further, especially if any basic assumptions utilized in this study are altered.

A.2.3. Modulation Technique

The discussion of modulation techniques is divided into consideration of digital and analog signals separately. Obviously, common elements are encountered since, for example, one method for transmission of an analog signal is to first digitize that signal.

A.2.3.1 Transmission of Digital Signals

In order to transmit digital data over RF links, appropriate signals must be selected for transmission through the medium. Two parameters are of interest: the bandwidth occupied and the bit error performance. The most commonly used techniques employ frequency or phase shift keying. The bit error performance of several of these techniques is shown in Figure A.2.3.1-1.

It is seen from the figure that the performance of the M-ary coded systems is better than that of binary systems; however, the bandwidth required for M-ary systems increases as $2^n/n$ where $n = \log_2 M$. The complexity of both transmitter and receiver hardware is increased; in the case of the receiver, the complexity goes up as 2^n ($2^{n/2}$ in the case of bi-orthogonal systems). As a consequence, the complexity of M-ary systems with $M = 16$ becomes prohibitive; the same improvement in bit error performance can be obtained more easily, and using less bandwidth, by means of binary or quaternary signals and using error correction coding.

Binary coherent PSK with a phase deviation of $\pm \pi/2$ gives the best performance of the binary signaling techniques. The modulator is extremely simple (a single double balanced mixer), whereas the demodulator implementation is somewhat more complicated, mainly because of the need for carrier recovery. The power spectrum of a RF carrier bi-phase modulated with a random NRZ data sequence is shown in Figure A.2.3.1-3. As a rule of thumb, the transmission bandwidth required is approximately equal to twice the bit rate.* With quadri-phase modulation the bit error rate performance is the same as with bi-phase modulation; however, the bandwidth required is cut in half, i.e., approximately equal to the bit rate.

The FSK curves shown in Figure A.2.3.1-1 assume a matched filter receiver with coherent and envelope detection, respectively. A simpler implementation is the limiter-discriminator receiver; however, its performance usually is worse

*The associated loss in performance due to band limiting is approximately 1 dB.

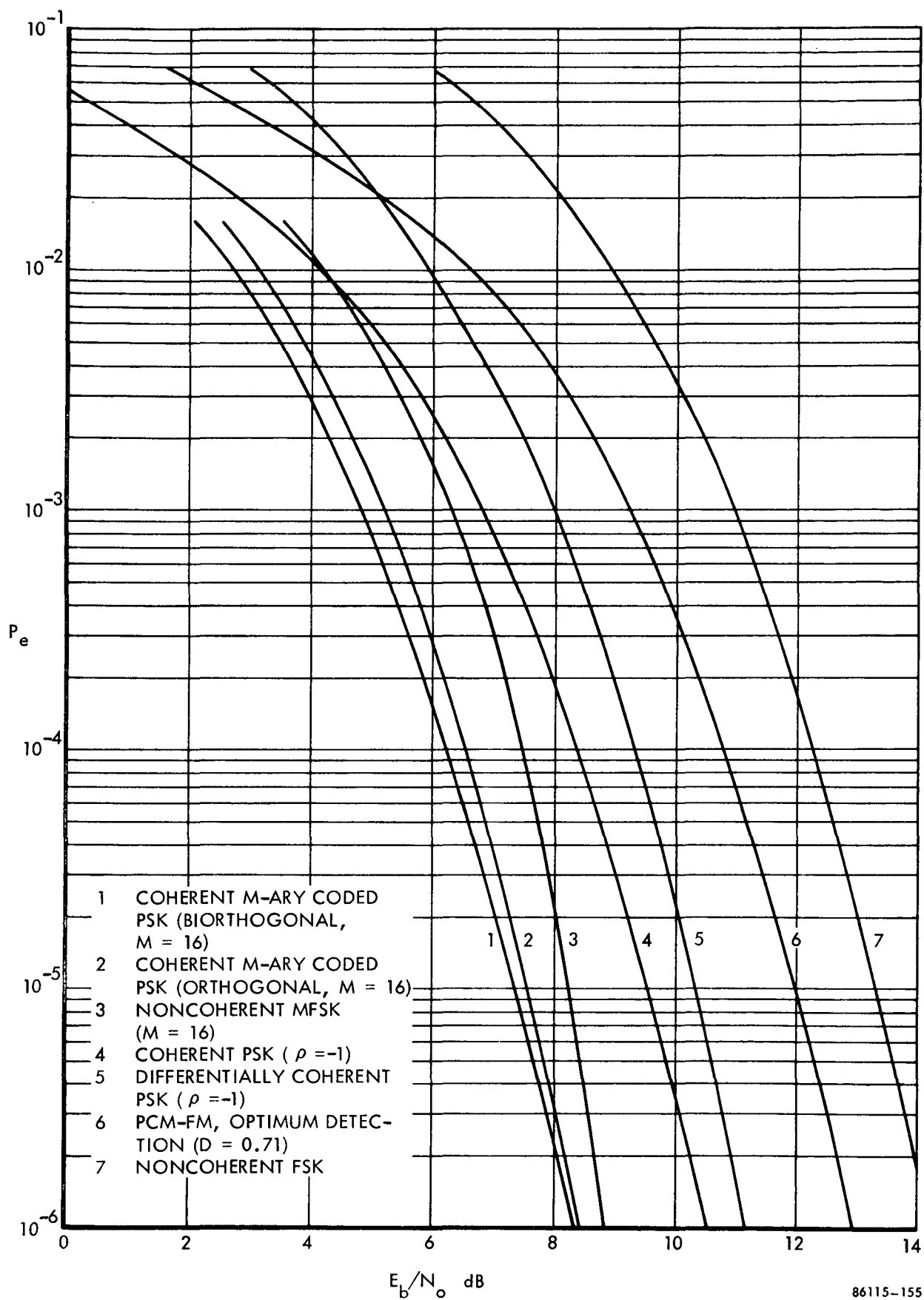


Figure A.2.3.1-1. Performance of Digital Modulation Systems

than that of the matched filter receiver. The spectra of FSK signals depend on whether they are generated by switching between oscillators or by applying a binary voltage to the VCO. The spectra for binary FSK with deviation ratios* of 0.5 and 1.0 are shown in Figure A.2.3.1-3.

Whereas the curves of Figure A.2.3.1-1 assume a detector operating on a bit-by-bit basis, some recent studies point out the fact that use can be made of the phase continuity from one bit to the next when the FSK signal is generated by a VCO. By considering two or three successive bits in making a decision, the performance can be made equal to or better than that for PSK with bit-by-bit detection. Bit error rate curves for FSK systems using different detection schemes are presented in Figure A.2.3.1-4. It is seen from Figures A.2.3.1-2 to A.2.3.1-4 that a bit error rate close to that for bi-phase PSK can be achieved by means of FSK using less than half the bandwidth, and that continuous phase FSK using two bit decisions is comparable to quadri-phase modulation (QPSK) in both bandwidth occupancy and performance. In fact, the spectrum of FSK with a deviation ratio of 0.5 rolls off faster than that of QPSK, and, therefore, less filtering is required if the available bandwidth is limited.

Another scheme, mentioned here only for completeness, is Amplitude Shift Keying (ASK). This technique is simpler to implement than any other digital modulation technique. The modulator is identical to the PSK Modulator and the demodulator is an envelope detector. The problem in using this scheme is the linearity requirement for the transmission path; power amplifiers are inherently inefficient when operated in the linear region.

It is concluded that PSK (bi-phase), QPSK, and continuous phase FSK are the most likely candidate digital modulation techniques for the application of interest. Bi-phase PSK is attractive because of its relative simplicity and good performance; however, in cases where the bandwidth is limited, QPSK or continuous phase FSK are preferable, giving comparable performance with reduced bandwidth occupancy, but requiring more complex modulators and demodulators.

A.2.3.2 Transmission of Analog Signals

Analog signals can be transmitted by means of either analog or digital modulation techniques. In general, analog modulation techniques require less

*The deviation ratio is defined as the ratio of peak-to-peak frequency deviation to bit rate.

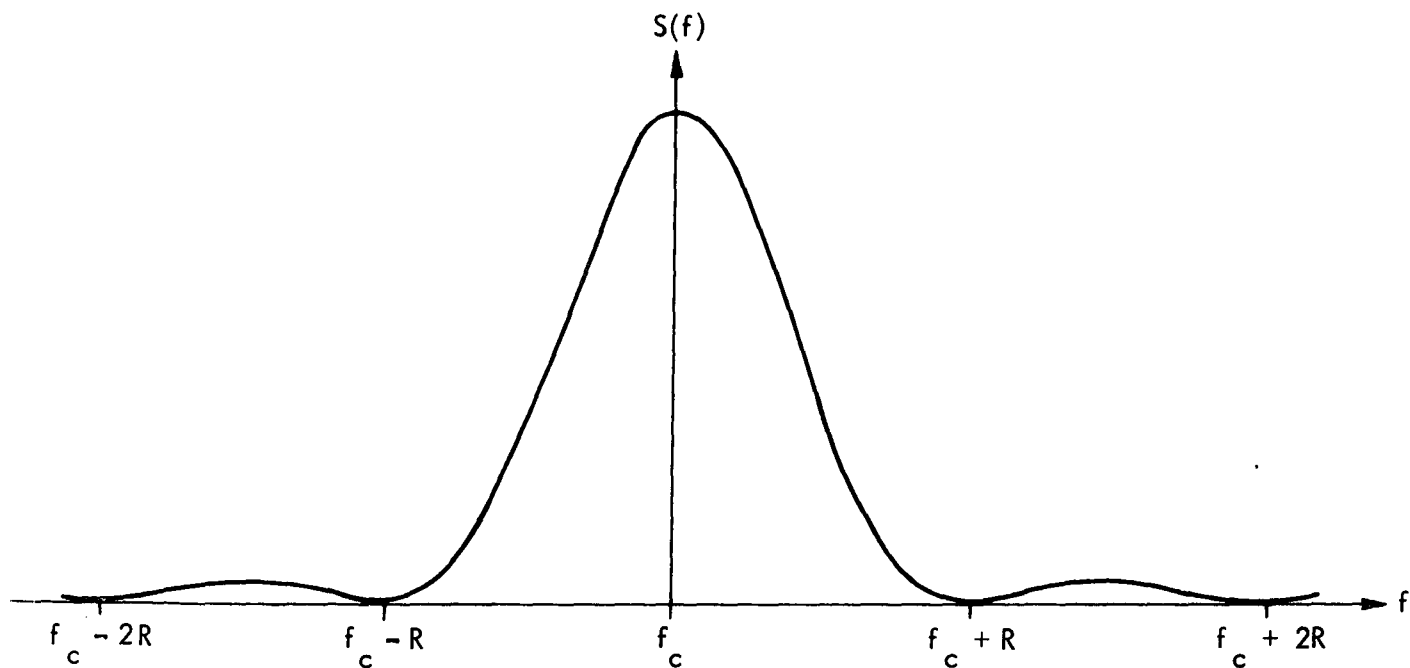


Figure A.2.3.1-2. Spectrum of PSK Signal (Bi-Phase)

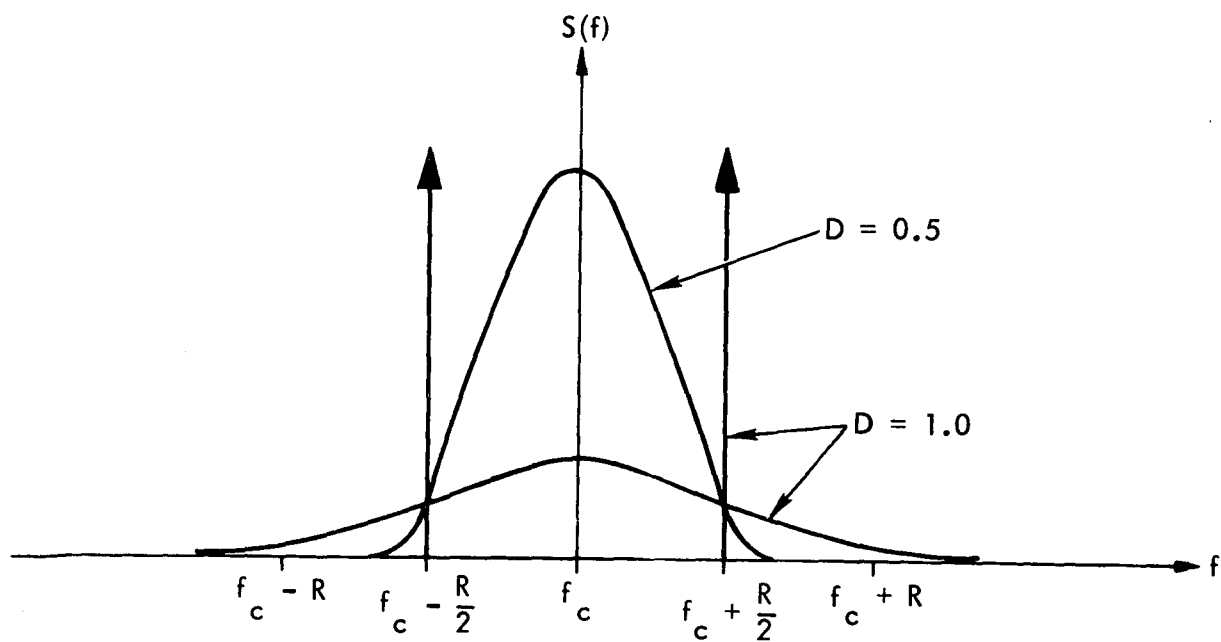
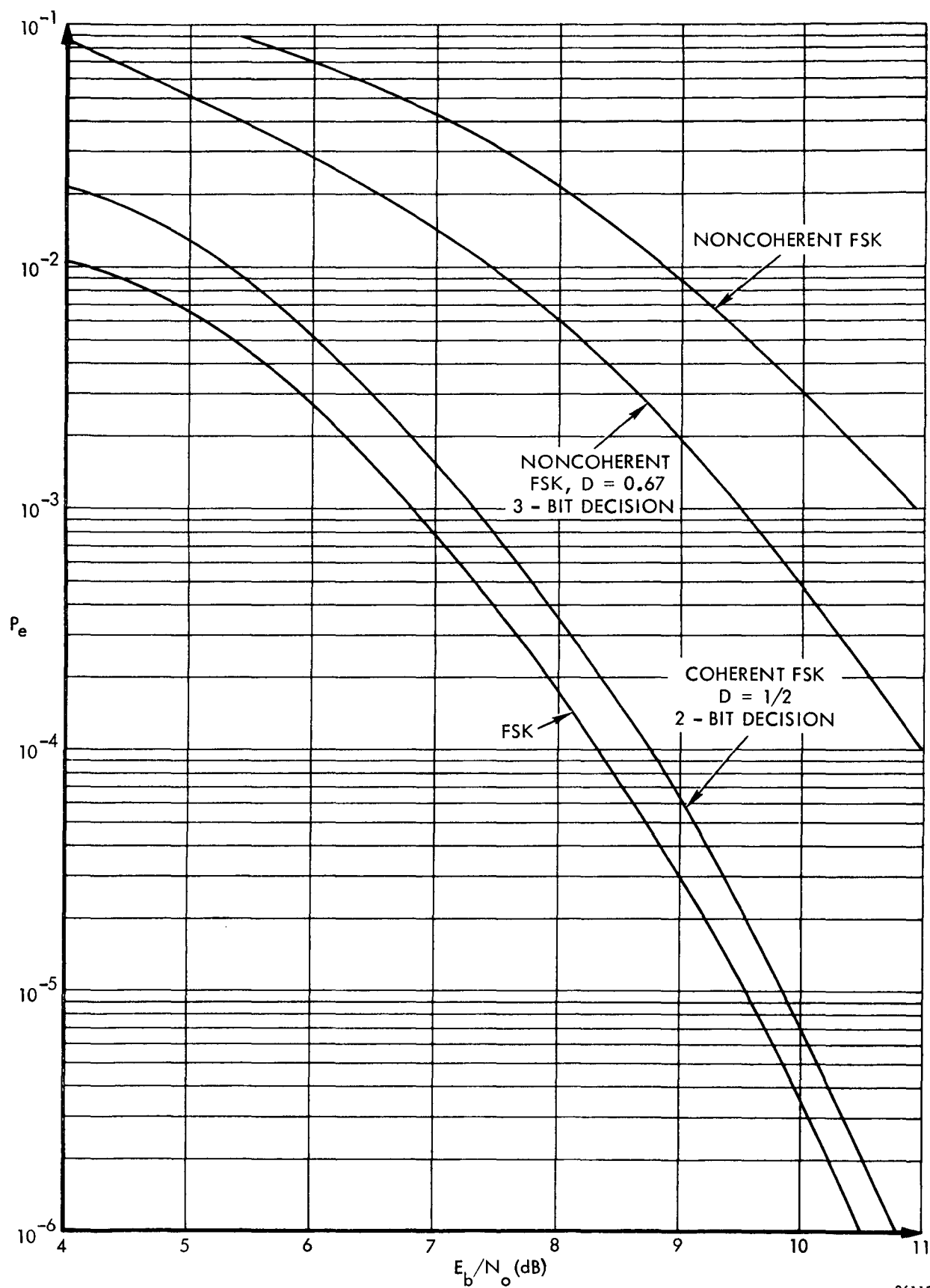


Figure A.2.3.1-3. Spectrum of FSK Signal

86115-156



86115-157

Figure A.2.3.1-4. Performance of FSK Systems

bandwidth to transmit a given baseband signal, but they usually require a higher signal-to-noise ratio. When analog signals are transmitted by means of PCM, analog-to-digital conversion equipment is required at the transmitter, and digital-to-analog conversion equipment is required at the receiver.

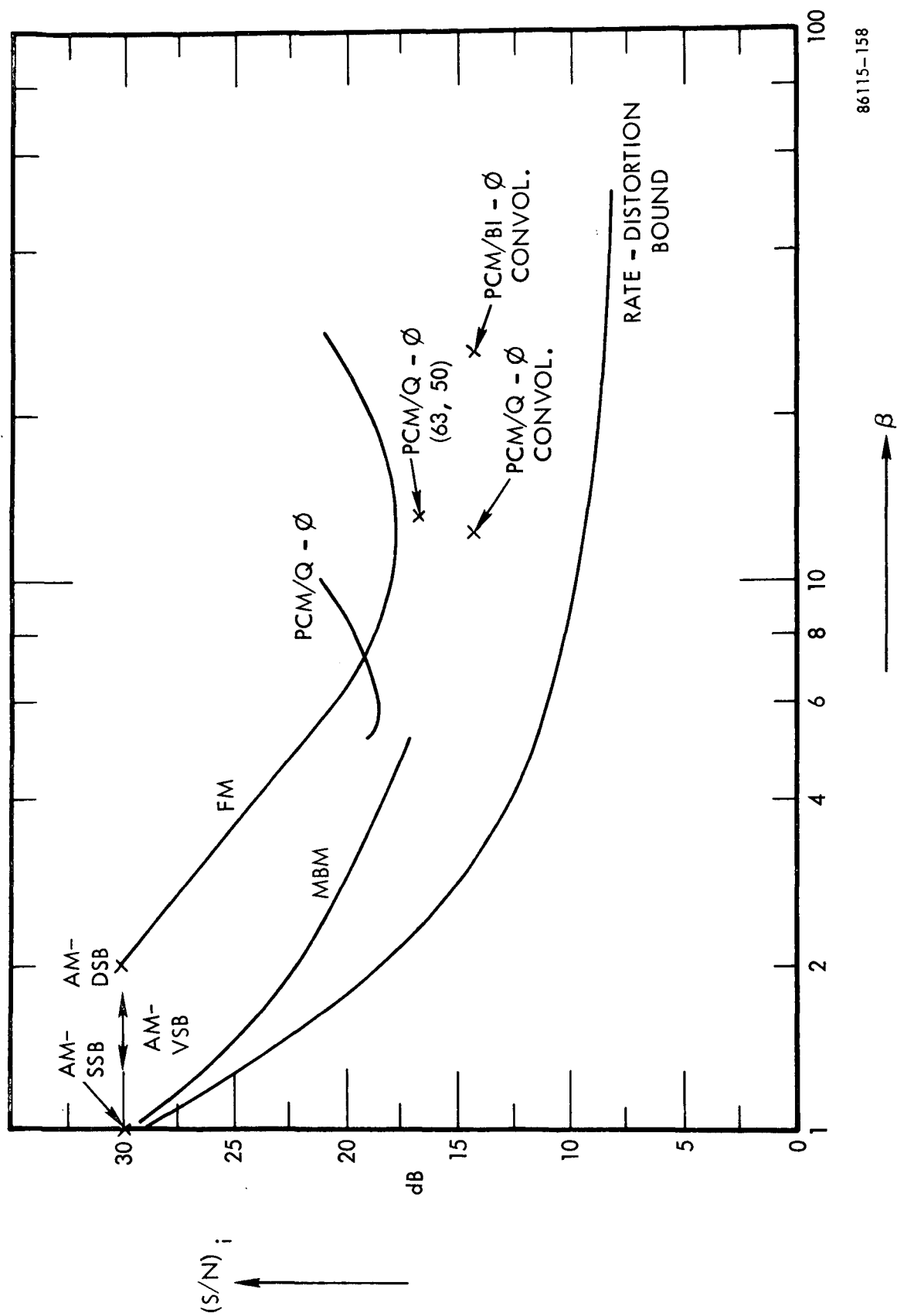
Since the bandwidth requirements in the ERTS type system are quite high, efficient utilization of the RF spectrum is an important consideration. Furthermore, it is seen from the link budgets that for Mode II links the signal-to-noise ratio appears to be relatively high thus possibly permitting the use of a modulation technique which uses less bandwidth at the expense of increased power.

A number of modulation techniques have been considered. These techniques are:

- Amplitude modulation (DSB, SSB, VSB)
- Frequency modulation (FM)
- Mixed base modulation (MBM)
- Pulse code modulation (PCM)

The performance of these modulation techniques can be expressed in terms of output signal-to-noise ratio as a function of input signal-to-noise ratio normalized to the baseband width), with bandwidth expansion as a parameter. Whereas amplitude modulation systems exhibit no signal-to-noise improvement, the other modulation techniques are non-linear and exhibit a signal-to-noise improvement, i.e., the output S/N is higher than the input S/N, at least for high input S/N. Non-linear modulation systems exhibit a threshold, i.e., for an input S/N less than a certain value (the threshold), the output S/N decreases rapidly. In FM and PCM systems the threshold is a function of the bandwidth expansion - the higher the bandwidth expansion, the higher the threshold. Mixed base modulation (MBM) is unique in that it offers a trade-off between S/N improvement and threshold for a fixed bandwidth expansion. Mixed base modulation can be viewed as quantizing the amplitude range of the signal to be transmitted into a number of intervals, with the interval number being transmitted in digital form and the remainder within the interval being transmitted in analog form. A more detailed discussion of this modulation technique is contained in Reference [31].

A signal-to-noise ratio of 30 dB is sufficient for most image system applications as the minimum quality of interest. In Figure A.2.3.2-1, the input



86115-158

Figure A.2.3.2-1. Modulation Systems Comparison for 30 dB Output S/N

signal-to-noise ratio (normalized to the baseband bandwidth) required to obtain 30 dB at the output is shown as a function of the bandwidth expansion, β . The figure also shows the rate-distortion bound which indicates the theoretical optimum.

It is seen that AM techniques are quite efficient at high signal-to-noise ratios. The difficulty with both AM and MBM is the linearity requirement for the transmission path*, currently available power amplifiers, such as TWTs, are rather inefficient when operated in the linear region.

A comparison of implementation complexity for the different modulation techniques is shown in Figure A.2.3.2-2. It is seen that the PSK systems require the least complex modulator and transmitter, whereas the demodulator is least complex for FM with discriminator detection. Implementation of the more efficient (in the sense of being closer to the ratio-distortion bound) techniques is seen to be considerably more complex. These complexity factors are discussed in Reference [18].

A.3 HIGH RATE INFORMATION STORAGE AND RETRIEVAL

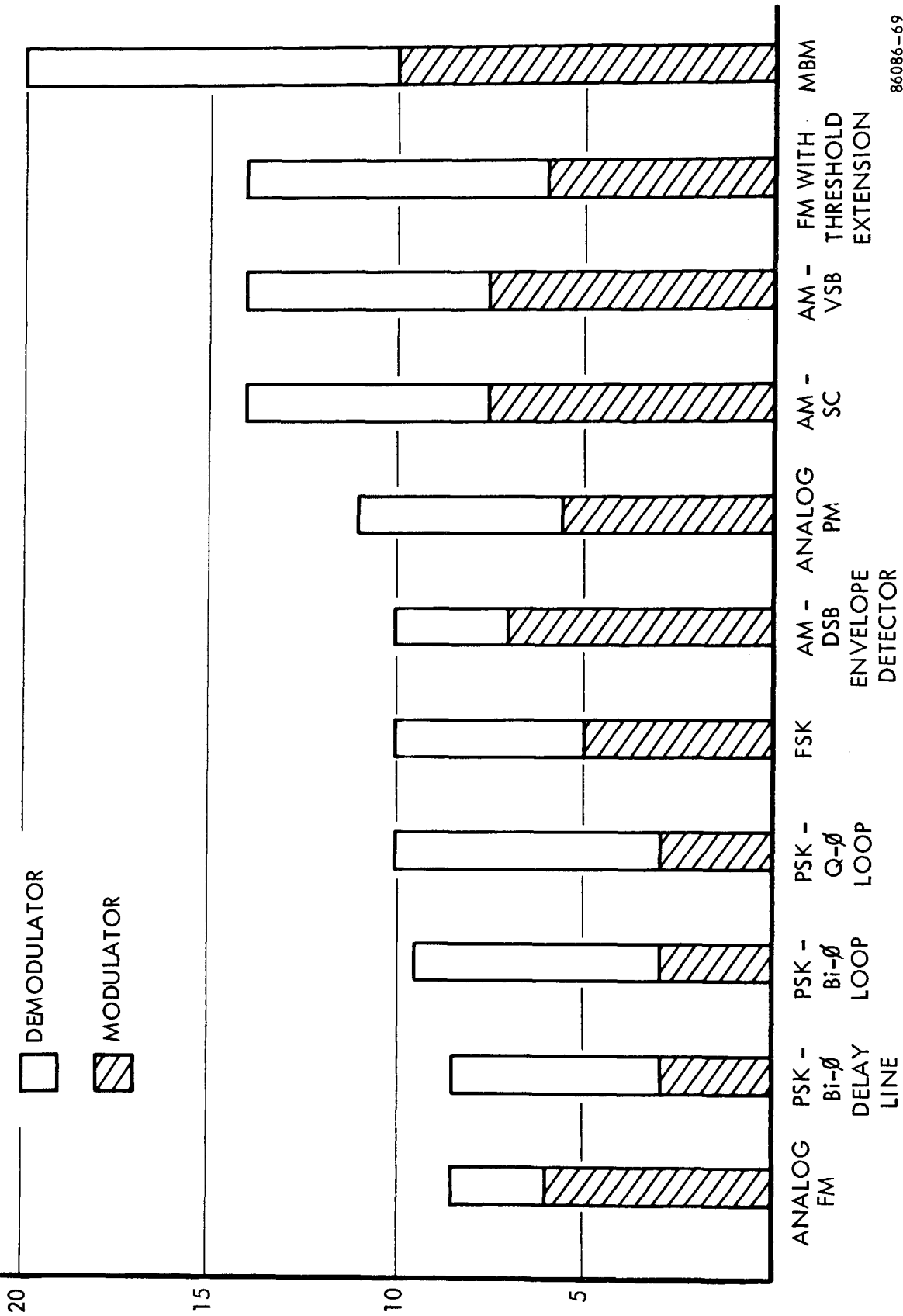
A recorder operating with data rates in the range from 50 to 200 Mb/s is required for the Regional Collection Center. Since this requirement is pushing state-of-the-art, especially for the maximum rates of concern, considerable study effort has been directed to recorder technology in the course of this effort. It has been determined that the high data rate recorder is presently the most questionable subsystem of the RCC. However, it is definitely feasible to record the rates of interest, but the eventual cost is sensitive to both data rate and development occurring on other programs. A recorder will probably be available off the shelf which will provide the required performance in the time frame of interest. Thus, the chosen technique is also dependent upon implementation time, the best (least risk, lowest cost) technique today may not be favored in 2 years.

The results of investigations in the high rate recorder area are discussed below. Three basic techniques have been considered as appropriate for 100 Mb/s recording rates:

1. Magnetic Tape
2. Laser/Film

*It is possible to configure on MBM system which operates with a saturating transmitter; however, the bandwidth expansion is doubled in that case.

RELATIVE
COMPLEXITY



86086-69

Figure A.2.3.2-2. Relative Implementation Complexity for Various Modulation Techniques

3. Electron Beam/Film

In considering magnetic tape recording, standard techniques are not sufficient especially if eventual reconstruction of a serial bit stream is required. Currently developed, high density multiple track methods will provide recording on a "channelized" basis to rates around 30-50 Mb/s per channel. Higher rates produce severe timing problems on signal reproduction. Everything considered, a magnetic approach using channelized recording with multiple tracks per channel is recommended if implementation were required now and for total rates of 100 Mb/s or below. For higher rates and/or in the 1973-75 time frame, other approaches (specifically laser/holographic) appear best.

Laser techniques include both direct and holographic recording approaches. Recorders with 50 MHz bandwidth have been developed and demonstrated and higher rates are very feasible. The holographic technique employing a cavity dump laser appears most promising for achieving 200 Mb/s rates and provides the advantages of reduced sensitivity to film scratches, etc., and a requirement for less precision in alignment of the optics.

Electron beam recorders have also been demonstrated which have some performance parameters consistent with the requirements. However, a limited error rate (10^{-4} BEP) has been demonstrated and this approach appears to be less promising than the others.

In making the survey described here, data from a number of potential vendors has been gathered. The primary sources of information have been Ampex and CBS Laboratories for electron beam techniques, CBS for laser recorders; and Ampex, General Dynamics, and RCA for magnetic approaches. In addition, Radiation is currently developing a high rate recorder utilizing laser recording and has previously developed a high density magnetic recorder. This experience has provided sufficient insight to allow accurate assessment of the state-of-the-art.

The following paragraphs summarize the results and conclusions of the high rate recorder survey.

A.3.1 Magnetic Recording Techniques

The use of magnetic tape recorders is in general limited to bit rates of 100 megabits per second or less. Several companies have demonstrated 100 Mbps capability including General Dynamics, RCA, and Ampex. Typical characteristics of the recorders are given in Table A.3.1-1.

Table A.3.1-1. Recorder Characteristics for High Rate Recording

Bits/inch/track	30,000 - 40,000*
No. of tracks	up to 32
Tape Speed	120 ips
Bit rate/track	3.6 - 4.8 Mbps
Tape Length	9200 feet (16" reel)
Record Time (at 120 ips)	15 minutes

*Ampex has recently demonstrated 50 Kb/inch/track in the laboratory.

Techniques are available to allow the use of magnetic tape recorders up to data rates of 200 Mbps, including the use of two recorders phase locked together to double the capacity. However, severe technical problems arise if the recorded data must be reconstructed into a serial data stream at playback, due to jitter and skewing of the tape as it passes the read heads.

This skewing of the tape as it passes the read head causes slippage of data between the various tracks. To correct the slippage, each track output must be buffered sufficiently to allow resynchronization before the data can be reconstructed into a serial data stream.

This timing and resynchronization problem is greatly alleviated if the data can conveniently be demultiplexed prior to recording such that no single signal of greater than 25-30 Mb/s rate must be reconstructed. Such a division is very convenient for this application.

Achievement of a bit error probability in the recording process of 10^{-6} is difficult without error correction coding. Since the goal for the system of interest is a system BEP of 10^{-6} , it appears that error correction encoding is required to achieve that goal. Block encoding techniques (see Section A.2) are most appropriate for the rates of interest. The required performance improvement can be realized with a modest bandwidth expansion. However, due to the data rates involved, the encoding should be performed on each channel. Thus processing to 25-30 Mb/s rates is required rather than to the 100-200 Mb/s total rate.

It should be pointed out that if encoding is to be utilized for the recorder subsystem, there is considerable merit in performing the coding function on the spacecraft. This would provide performance improvement for the total system.

A.3.2 Laser Recording Techniques

Laser/Film recorders are being developed that have a wide bandwidth and high density storage capability. CBS Laboratories has developed a 50 MHz bandwidth recorder using a laser recording on a five inch film strip. They indicated that a 100 MHz recorder was feasible, although it has not been developed at this time. It was indicated by CBS that the most promising approach to record at 200 Mbit/sec data stream would be to use a zone lens holographic technique. Estimated development costs were \$300K with a cost of approximately \$150K per system. No details of this system were obtainable at this time.

Radiation is presently developing techniques for real-time recording of data rates up to 1000 megabits per second with packing densities in excess of 10^6 bits/cm². A holographic electro-optic approach using photographic film as the recording medium is being investigated. The advantages of holographically recording high density data include:

- Reduced bit dropout, caused by surface scratches, dust, or other contaminants that may be experienced by the film, because holograms possess a redundancy property.
- Reduced precision alignment requirements, because the lateral motion of holograms has little effect on the position of the readout image.

The most promising approach presently being investigated employs an acousto-optic module as a Bragg cell to modulate the laser beam at rates between 20 and 40 megabits/second. Higher data rates are achieved by using ten or more cells simultaneously.

For this application the capability of a single acoustic cell is well aligned with the per channel data rate. Thus, the best approach would be similar to that used with the magnetic recorder in which the input serial stream is demultiplexed into several channels where each channel corresponds to a single spectral band of image data. Another advantage of this holographic laser approach is the relative simplicity possible in the playback system. A less complex system than the recorder

can be used to reproduce the input data at arbitrary rates. Therefore, the processing center hardware would be relatively simple and the input rate to the processing system could easily be controlled and varied to match the needs of the processor.

For the holographic laser techniques, as with magnetic recording, the BEP goal of 10^{-6} is optimistic. A more realistic number in the absence of error correction encoding is 10^{-4} to 10^{-5} . A more reliable estimate will be available within the next year as Radiation expects to have constructed a prototype system within that time frame.

A.3.3 Electron Beam/Film Techniques

Several companies have produced or are developing electron beam recorders using film as the recording medium. CBS Laboratories is providing electron beam recorders for ERTS A/B under contract with Bendix. These are video recorders with a 40 MHz bandwidth.

In addition, Ampex has developed and demonstrated an electron beam recorder with a 100 MHz frequency response.* This recorder can record up to 10 minutes of analog data on a 3700 foot long 35 mm film strip. They predicted a capability to record digital data at a rate of 150 megabits/second with an error rate of 10^{-4} .

A.3.4 Conclusions

While techniques are available or are being developed that will allow direct recording at rates up to 200 megabits/second, it would appear cost effective to demultiplex the data and use existing hardware for the ERTS DRGS recorder application. Since it can be assumed that the data source can be demultiplexed into channels representing spectral bands of approximately 30 megabits/second or less, relatively simple configurations utilizing existing magnetic recorders can be obtained.

This approach would use an existing recorder such as an Ampex FR1900 or equivalent. A spectral band would be demultiplexed into seven channels, coded, and converted to NRZ data for recording on a seven track head. Upon playback each track would be NRZ₀ decoded, error correction decoded, and remultiplexed

*See "Electron Beam Instrumentation Recorders", C. F. Spitzer and J. P. Diermann, Proceedings of the 24th Annual Conference of the Instrument Society of America, October 1969.

into a 30 megabit per second data stream. Additional channels could be added by adding additional heads to the recorder and additional electronics for multiplexing, coding, decoding, and demultiplexing the data. A reasonable upper limit to the number of spectral bands per recorder is three, with four being possible.

The deskewing problem is considerably simplified by this approach since only seven tracks on the same head would have to be deskewed for each channel.

This approach, due to its modularity, allows easy expansion of the recording capability of the DRGS by adding additional recorders and channels as required. It also makes maximum use of existing hardware, thus minimizing development costs.

If the data cannot be channelized, but must be reconstructed into a serial data stream upon playback, the most promising approach would appear to be the use of a holographic laser recorder. This hardware is not available at this time, but could be developed within a relatively short time.

As noted previously, the holographic laser recorder technique is consistent with the channelized recording approach which has merit for this application. Therefore, if development of the laser recorder progresses as expected, it could easily be the most cost effective recorder approach when the system is implemented.

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